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Mach number, flow angle, and loss measurements downstream of a transonic fan-blade cascade

Austin, Jeffrey G.

Monterey, California. Naval Postgraduate School

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MACH NUMBER, FLOW ANGLE, AND LOSS MEASUREMENTS
DOWNSTREAM OF A TRANSONIC FAN-BLADE CASCADE

By

Jeffrey G. Austin

March 1994

Thesis Advisor: Raymond P. Shreeve

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Two dimensional flow measurements of Mach number and flow angle were conducted downstream of a transonic fan-blade cascade at a Mach number of 1.4 to provide baseline data for assessing the effect of vortex generating devices on the suction surface shock-boundary layer interaction. The experimental program consisted of the design and calibration of a traversing three-port pneumatic probe to measure Mach number and flow angle and initial cascade measurements to provide baseline data for the fully-mixed-out total pressure loss coefficient and flow turning angle. Similar tests are planned with the vortex generating devices installed. Comparisons with and without the vortex generating devices are needed to quantify the overall effect on the shock-boundary interaction in a transonic fan-blade passage, and to assess the potential for using vortex generating devices in military engine fans.

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Mach Number, Flow Angle, and Loss Measurements Downstream of a Transonic
Fan-Blade Cascade

by

Jeffrey G. Austin
Lieutenant, United States Navy
B.S., University of Puget Sound, 1985

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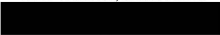
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Jeffrey G. Austin

Approved by: _____
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_____
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_____
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Department of Aeronautics and Astronautics

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ABSTRACT

Two dimensional flow measurements of Mach number and flow angle were conducted downstream of a transonic fan-blade cascade at a Mach number of 1.4 to provide baseline data for assessing the effect of vortex generating devices on the suction surface shock-boundary layer interaction. The experimental program consisted of the design and calibration of a traversing three-port pneumatic probe to measure Mach number and flow angle and initial cascade measurements to provide baseline data for the fully-mixed-out total pressure loss coefficient and flow turning angle. Similar tests are planned with the vortex generating devices installed. Comparisons with and without the vortex generating devices are needed to quantify the overall effect on the shock-boundary interaction in a transonic fan-blade passage, and to assess the potential for using vortex generating devices in military engine fans.

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LIST OF SYMBOLS

a_0-a_6	Coefficients of Eq. (5)
b_0-b_3	Coefficients of Eq. (6)
C_p	Specific heat at constant pressure
d_s	Distance of one blade space
d_1	Staggered passage width
M	Mach number
P	Pressure
P_T	Stagnation (total) pressure
P1	Probe pressure (center tube)
P2	Probe pressure (side hole-facing down)
P3	Probe pressure (side hole-facing up)
P23	Average of P2 and P3
T_T	Stagnation temperature
V	Velocity
V_T	Limiting velocity
X	Dimensionless velocity
B	Defined by Eq. (3)
β_i	Flow angle
γ	Ratio of Specific Heats
Γ	Defined by Eq. (4)
θ	Flow angle to the probe axis (and to inlet flow direction)
ϕ	Pitch angle
Φ	Pitch angle at X_i=constant

ϖ Mass-averaged loss coefficient

ω_{mixed} Mixed-out loss coefficient defined in Appendix E, Eq. (13)

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I. INTRODUCTION

The requirement to achieve higher compressor ratios in the fan stages of military and civilian engines has led to increasing supersonic relative inlet Mach numbers. The higher Mach numbers lead to stronger shock waves forming in the rotor passages near the blade leading edge. These strong shocks interact with the turbulent boundary layer on the suction side of each blade to produce the flow field depicted in Figure 1.
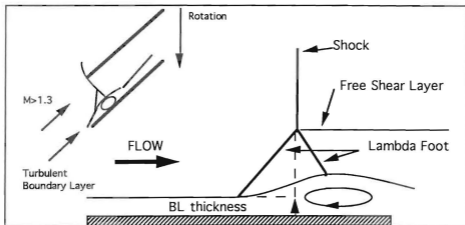
Figure 1. Shock-Boundary Layer Interaction

The shock-boundary layer interaction is characterized by the lambda foot and a local region of reversed flow. The strong shock-boundary layer interaction adversely effects the total pressure ratio and flow turning angle of the compressor blade row. A concept for alleviating the shock-induced boundary layer separation is the use of low-profile vortex generators affixed to the suction surface of the rotor blading, some distance ahead of where the shock impinges.

Vortex generator devices alleviate the shock interaction by energizing the low momentum region of the boundary layer with relative near-freestream flow via streamwise vortices. The vortex generators reduce the relative total pressure loss in the rotor by reducing the size of the local separation and also improve the flow turning angle toward that required by the design. In the present study, 6-5-1 "Triangular Plow Vortex Generators", depicted in Figure 2 and described by McCormick [Ref. 1] and United Technologies Research Center [Ref. 2], were to be used in a model transonic Fan-Blade cascade to quantify their effect on the total pressure losses and flow turning angle and thereby assess the potential benefits of this technique.
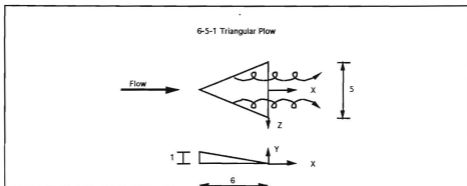
Figure 2.   Low-Profile Vortex Generator

The model cascade apparatus was first assembled and operated by Collins [Ref. 3]. First successful static pressure measurements were made by Golden [Ref. 4] and impact probe traverse measurements by Myre [Ref. 5]. Tapp [Ref. 6] showed that repeatable periodic conditions could be achieved at the design flow angle using wall bleed. In the present study, a three-port traversing pneumatic probe was designed, calibrated, and used to measure dimensionless velocity and

flow angle over the outlet of a blade passage. These values were used to calculate a fully-mixed-out condition, and hence the total pressure loss and flow turning angle. A follow-on study will apply the techniques reported here to assess the effects of vortex generators. In the present document, Chapter II describes the design and calibration of the three-port probe and the transonic fan-blade cascade model. Chapter III describes the experimental program and test results. Chapter IV includes the conclusions and recommendations for further work.

II. EXPERIMENTAL DEVELOPMENTS

A. PROBE DESIGN

To measure Mach number and flow angle behind the model fan-blade passage required a probe that was sensitive to only Mach number and pitch angle, since the yaw angle was zero at mid-span. It was desirable (though not necessary) that the arrangement of sensors would result in two pressure coefficients such that one was insensitive to changes in pitch angle at constant Mach number and the other insensitive to changes in Mach number at constant pitch angle. AGARD-AG-207 [Ref. 7] reported probe designs that had such characteristics, which guided the present design shown in Figure 3.
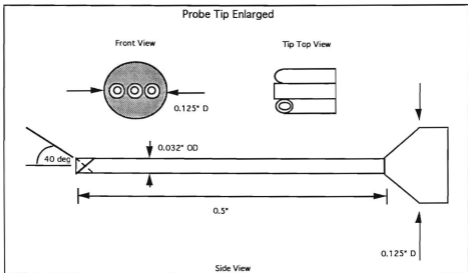
Figure 3.   Probe Tip Enlarged

Additionally, the probe was required to measure velocities in a shear layer as it traversed through the fan-blade wake, which required that the ports all lie in the same plane. Myre [Ref. 5] developed a traversing impact probe system for use in the present experiment with the ability to accommodate different probe tips. The present probe was designed to fit the existing probe holder and traverse system for use with the current data acquisition system hardware and software reported by Myre [Ref. 5]. A three-port pneumatic probe was chosen using 0.032" OD stainless steel tubing. The center port was cut normal to the tunnel axis with the outer two ports shaved to an angle of approximately forty degrees in opposite directions.

B. PROBE CALIBRATION

The probe calibration was carried out in the Turbopropulsion Laboratory's free-jet calibration apparatus which is shown in Figure 4. The probe holder assembly is described by Myre [Ref. 5] and depicted in Figure 5. The nozzle of the free-jet was 4.25 inches in diameter and was fed by an Allis-Chalmers compressor delivering air at a pressure of up to three atmospheres. The Mach number range of the free-jet, which exhausted to atmosphere, was from 0 to 0.9. The probe holder was attached to an apparatus mounted to the free-jet nozzle which allowed the operator to accurately set and vary the pitch angle of the probe, as required for the calibration. A Prandtl probe was installed 0.5 inches from the jet centerline to provide redundancy in the measurement of Mach number.
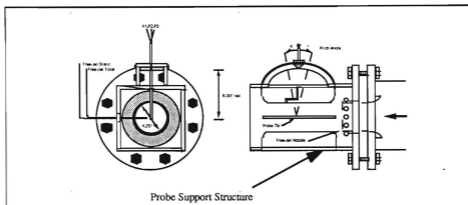
Figure 4. Free-Jet Calibration Apparatus
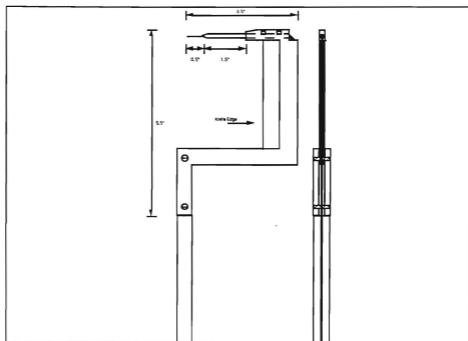
Figure 5. Probe Holder Assembly

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1. **Data Acquisition System**

The pressure measurements of the probe (3), free-jet static pressure (atmospheric), and free-jet total pressure were acquired using a +/- 50 psid Scanivalve transducer controlled by a Hewlett-Packard 9000-300 series computer. The HP 9000 computer sent commands via a HG-78K Scanivalve controller developed by Geopfarth [Ref. 8] to the Scanivalve. It in turn sent the measured voltage of the transducer to a HP 3456A digital voltmeter, which was read by the computer. The voltages were recorded and converted to psia in an HP BASIC data acquisition program, "CAL_ACQ", listed in Appendix A. Golden [Ref. 4] describes in detail the use of the data acquisition system.

2. **Program of Measurements**

The impact probe and probe assembly were removed from the transonic cascade and the new three-port probe design was installed. The new probe and probe holder assembly were mounted in the free-jet calibration apparatus. The probe was leveled in its mount, then securely fastened in place. The probe tip was located at the center of the free-jet, which has been shown to have a uniform velocity profile by Neuhoff [Ref. 9]. The free-jet static and total pressures were used to calculate the jet Mach number and limiting velocity using isentropic gas relations with the ratio of specific heats equal to 1.4. The relation between total (stagnation) pressure, static pressure, and dimensionless velocity is

$$\frac{P}{P_T} = \left(1 - X^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

where

$$X = \frac{V}{\sqrt{2C_p T_T}}$$

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The Mach number was held stable while 12 pitch angles were set in turn and pressure data were recorded. The Mach number was varied in steps of 0.1 from M = 0.2 to 0.9, giving a total of 96 calibration data points. In the calculation of dimensionless velocity the center port pressure measurement was taken to be total pressure since it was always in the center of the flow and always read slightly higher than the Prandtl probe total pressure. The static pressure was taken to be atmospheric, which was consistent with the Prandtl probe measurements. The raw data from the calibration are listed in Table B1 and Table B2 of Appendix B.

3. Probe Characteristics

The derivation of the probe pressure coefficients followed the work of Neuhoff [Ref. 9]. If P1 is the pressure at the center port and P2 and P3 are the pressures of the two side ports, we define the average of P2 and P3 as P23, where

$$P23 = \frac{P2 + P3}{2} \tag{2}$$

and the two pressure coefficients used to represent the calibration of the probe in terms of Mach number and pitch angle are

$$\text{Beta} = \text{B} = \frac{P1 - P23}{P1} \tag{3}$$

and

$$\text{Gamma} = \Gamma = \frac{P2 - P3}{P1 - P23} \tag{4}$$

The measured characteristics of the probe in terms of Beta and Gamma are shown in Figures 6 and 7 respectively. The Mach-sensitive coefficient Beta

was found to be relatively insensitive to changes in pitch angle over the entire Mach range. The pitch sensitive coefficient Gamma was found to be relatively insensitive to changes in Mach number over the range of pitch angles.
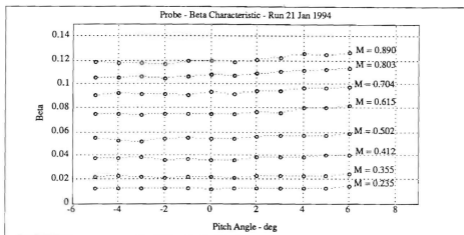
Figure 6.   Beta Characteristic
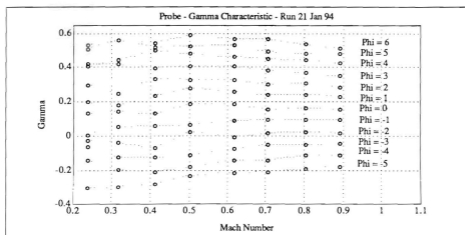
Figure 7.   Gamma Characteristic

The insensitivity of Beta to pitch angle allowed the Mach number and dimensionless velocity, X, to be approximated by a polynomial in terms of Beta only. The polynomial for X as a function of Beta was derived utilizing the least-squares method, using an average value of Beta over the range of pitch angle. The program MATLAB was used to determine this polynomial and a choice of a sixth-order polynomial was found to give the least error in X over the calibration range. The polynomial is shown as Equation 5, with the values of the coefficients listed below. The sixth-order polynomial is shown and plotted vs. the actual data points in Appendix C.

$$X = a_6 B^6 + a_5 B^5 + a_4 B^4 + a_3 B^3 + a_2 B^2 + a_1 B + a_0$$
$$a_6 = -1733913.202$$
$$a_5 = +679216.632$$
$$a_4 = -104416.881$$
$$a_3 = +8119.488 \tag{5}$$
$$a_2 = -344.912$$
$$a_1 = +10.120$$
$$a_0 = +0.018$$

A third-order polynomial for pitch angle was derived in terms of Gamma at each average dimensionless velocity using the least-squares method and the MATLAB software. The polynomial has the form of Equation 6 with the coefficients summarized in Table 1. The third-order polynomials of pitch angle in terms of Gamma are plotted vs. the actual data points in Appendix C.

$$\Phi_i = b_3 \Gamma^3 + b_2 \Gamma^2 + b_1 \Gamma + b_0 \tag{6}$$

where X_i = constant

TABLE 1. PROBE CALIBRATION COEFFICIENTS

	X_i	b_3	b_2	b_1	b_0
Φ_1	0.1047	-0.815	3.584	12.251	-1.841
Φ_2	0.1397	0.156	0.412	12.112	-1.548
Φ_3	0.1812	19.817	-5.526	9.996	-1.461
Φ_4	0.2192	13.149	-3.288	11.104	-1.973
Φ_5	0.2650	15.897	-5.546	12.155	-2.072
Φ_6	0.3002	3.438	0.520	13.270	-2.268
Φ_7	0.3378	11.242	-2.607	13.736	-2.349
Φ_8	0.3698	11.968	-3.634	14.607	-2.347

4. **Application of the Calibration**

The method of application of the calibration was first to take the measured probe pressures and determine the coefficients Beta and Gamma. From the Beta coefficient, the dimensionless velocity could be determined immediately using the sixth-order polynomial. With the dimensionless velocity known, the third-order polynomials of pitch angle in terms of Gamma could be calculated for the curves associated with the values of the dimensionless velocity above and below the calculated dimensionless velocity. An interpolation scheme given by Nakamura [Ref. 10] was then used to interpolate for the pitch angle at that known velocity and value of Gamma. The results of applying the calibration method to the actual data is given in Appendix C. Over the entire range of the calibration the uncertainty in dimensionless velocity was found to be +/- two percent with a confidence of 70 percent. The pitch angle uncertainty was found

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to be +/- 0.2 degrees with a confidence of 76 percent. Above a dimensionless velocity value of 0.18, the confidence level increased due to the improved resolution of the data acquisition system at the higher velocities. Above this velocity, where most of the cascade measurements were to be taken, the confidence in determining dimensionless velocity and pitch angle accurately rose to 73 percent and 96 percent respectively. A Kline and McClintock uncertainty analysis [Ref. 11] was performed and at the lower velocities, X< 0.18, the uncertainty in Beta and Gamma was much higher than at the higher velocities. This explains why the calibration scheme is more accurate at the higher velocities and why the Gamma characteristic behaves poorly at lower velocities. The calibration application program, written in Hewlett-Packard Basic is listed in the data reduction program "NEW_READ_ZOC1", in Appendix D.

C. TRANSONIC CASCADE MODEL AND DATA ACQUISITION

1. Transonic Cascade Model

The transonic cascade model attempts to simulate the relative flow at M=1.4 on a stream surface through a Navy developmental transonic fan. The current model has been shown by Golden [Ref. 4] to be closely two dimensional with the placement of the shock structure set manually using an in-line shadowgraph while adjusting back pressure and bleed valves. The vertically-traversing probe assembly designed by Myre [Ref. 5] was used with the new probe design. Myre also describes the use of the traversing system [Ref. 5]. The wind tunnel facility is shown schematically in Figure 8. The transonic cascade model test section is shown in Figure 9. The model simulation is of the flow through two passages of the transonic blading geometry which is shown in Figure 10. In the cascade simulation, the design pressure ratio and shock

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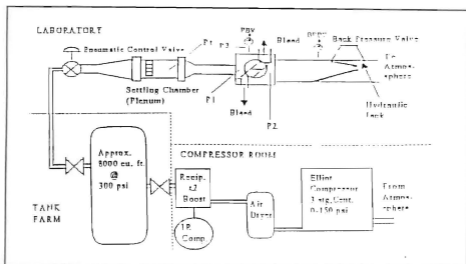
Figure 8. Wind Tunnel Facility
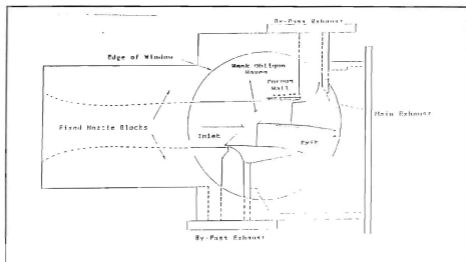
Figure 9. Transonic Cascade Model Test Section

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structure at the design incidence were set using the "Back-Pressure Valve (BPV)". A "Back-Pressure Bleed Valve (BPBV)" was used for fine adjustments in setting the proper shock structure (Figure 8).

2. Data Acquisition System

The data acquisition system utilized in the present study was used previously by Tapp [Ref. 6]. One +/- 50 psid ZOC-14 enclosure was used to record the three pressures of the traversing probe. Plenum and wall reference pressures were also recorded. The data acquisition program "NEW_SCAN_ZOC" [Ref. 5] was modified slightly to allow the probe-traverse mechanism to increment in smaller steps through the wake, in order to improve the spatial resolution. To change the increment step size required a change in only a single line of code. The initial starting point of the probe-traverse assembly was also changed by a single entry.

The data reduction program "READ_ZOC2" [Ref. 5] was modified for use in the current study and renamed "NEW_READ_ZOC1". The principal change was the application of the routine to return dimensionless velocity and flow angle from the three pressure measurements. The calculation of the fully-mixed-out condition was also calculated in the program. The program is listed in Appendix D and the calculation of the fully-mixed-out condition is summarized in Appendix E. A complete derivation of the method for calculating the fully-mixed-out dimensionless velocity, flow angle, and total pressure is contained in Reference 12.

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W1

W2

β1 β2

Axial

$\beta 2 - \beta 1 = -\theta$

Probe Measures θ

Blade Geometry

L.E. Radius   = 0.015"
T.E. Radius   = 0.015"
L.E. Wedge Angle= 3.5 deg
T.E. Wedge Angle= 10.56 deg
Wedge Length   = 2.85 "
Suction Surface = 13.53 "
Arc Radius

6.0"

M=1.4

1.15 deg

1.656"

3.0"

51.84 deg

β1=56.49
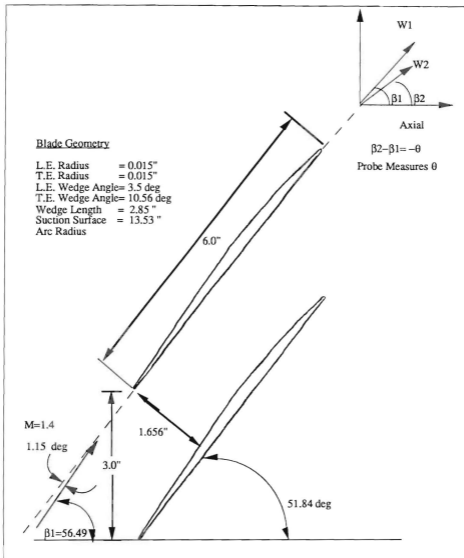
Figure 10.   Cascade Blading Geometry

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III. EXPERIMENTAL PROGRAM, RESULTS AND DISCUSSION

A. EXPERIMENTAL PROGRAM

The experimental program consisted of a series of initial runs with equal-increment probe traverses through the center blade wake. These tests were used to refine the operation of the pressure valves in setting the shock structure, to become familiar with the data acquisition procedures, and to verify the revised coding of the data reduction program "NEW_READ_ZOC1". Repeatability tests were then conducted to verify that the impact probe measurements compared with previous results reported by Myre [Ref. 5] and Tapp [Ref. 6]. Once these tests were completed the number of data points in the blade wake was increased to provide better resolution through the wake. These tests were used to examine probe-derived static pressure and angle distributions through the wake. Finally, five tests were conducted to provide baseline data and to establish the fully-mixed-out condition for use in studies to assess the effect of vortex generating devices. In all the tests, the shocks in the upper and lower passages were repeatedly set to the expected on-design position, using the following procedure:

- 1. The tunnel was allowed to become steady at a plenum pressure of 33 psig.

- 2. While carefully monitoring the shadowgraph, the BPV was closed by four smooth movements of the hydraulic jack handle.

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- 3. A fifth movement of the jack handle (done smoothly) was stopped just as the lower passage shock was in position at a mark on the tunnel side plate (visible in the shadowgraph).

- 4. The BPBV was closed until the upper passage shock was in the corresponding position. Its position was monitored visually throughout the data acquisition during the probe traverse.

B. REPEATABILITY TESTS

These tests were run to compare the mass-averaged loss coefficient results obtained with the new probe and those obtained by Myre [Ref. 5] and Tapp [Ref. 6], using an equal-increment traverse procedure, across a distance of two inches. The probe tip was approximately 1 1/8 inches downstream of the trailing edge of the middle blade with the probe starting its traverse 1.0 inch above the level of the blade trailing edge. Figures 11 and 12 show the blade-wake pressures vs. vertical position during the traverse. Table 2 summarizes the results of tests in which tunnel supply conditions were held reasonably constant.

TABLE 2. REPEATABILITY TESTS: 2/24/94 RUN 2 AND RUN 4

Run #	Patm (psia)	P2/P1	$T_T(R)$	ϖ
2	14.72	2.11	514.5	0.0842
4	14.715	2.09	513.0	0.0847

The raw pressure data for the complete test program are listed in Appendix F. The mass-averaged losses compared well (to within three percent) with previous results [Ref. 5 & 6] with similar tunnel conditions. The data confirmed that the

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probe, data acquisition system, and data reduction process were operating properly.
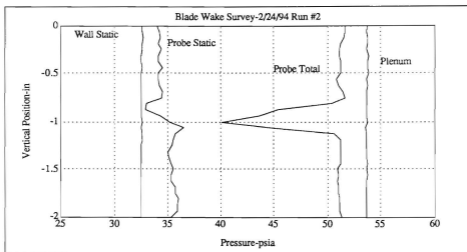
Figure 11. Blade Wake Survey: 2/24/94   Run 2
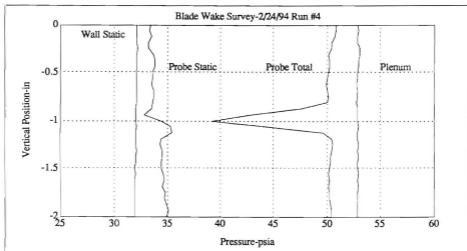
Figure 12. Blade Wake Survey: 2/24/94   Run 4

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Probe-derived static pressure profiles are shown in Figures 11 and 12. It is seen that the static pressure on the suction side of the blade was lower than that on the pressure side, implying a higher velocity in that portion of the upper passage. A change in static pressure through the wake can clearly be seen. Both runs show a reasonably periodic condition in the cascade model based only on the measured total pressure.

C. TURNING ANGLE DISTRIBUTION

Figure 13 shows the distribution of the flow angle derived from probe measurements in three similar tests.
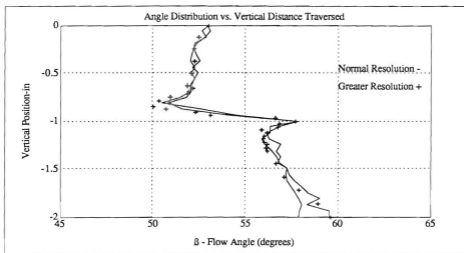
Figure 13. Angle Distribution Comparison

Figure 13 contains data from Runs 2, 4, and 5 of 2/24/94. As presented previously, Runs 2 and 4 were equal-increment surveys for a two inch traverse. Run 5 was a survey which stepped 0.03125 inches per increment through 22 points just prior to, and through the blade wake, providing better spatial

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resolution. The start and end points remained the same for all three runs. The data are seen to be similar for all runs. The angle distribution is characterized by increased values of outlet flow angle (β_2) from the upper portion of the lower passage (less turning). The value of β_2 from the upper passage approaches that of the design value of 50 degrees. The flow angle behaves similarly to the static pressure through the turbulent blade wake. Without further measurements, the differences in flow angle and dimensionless velocity cannot be explained definitively. The higher turning angle in the upper passage and lower turning angle in the lower passage is most probably the result of the significant differences in the wakes of the center and lower blades. The center blade is a true blade wake, the lower blade wake is a mixing layer, with entrainment from the test section cavity. In viewing the probe distributions, it should be remembered that the traverse was not parallel to the blade trailing edges so that the lower part of the traverse is further downstream of the blading than is the upper part. The data do show that the angle distributions through the passages were repeatable.

D. PROBE STATIC PRESSURE DISTRIBUTION

Figure 14 shows a comparison of probe-derived static pressure for the same tests as in Figure 13. The static pressure distributions all have the same form, and were reasonably repeatable. The improved resolution blade-wake surveys clearly show a steep decline in static pressure as the probe entered the blade wake, then a sharp rise through the wake. The static pressure rises slightly again on the pressure side of the blade wake, then stabilizes at a value above that of the upper passage.
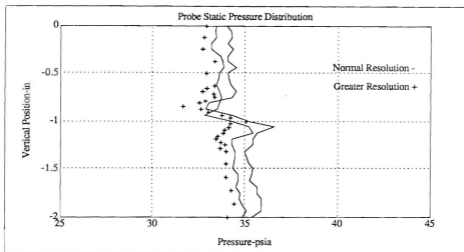
Figure 14. Probe Static Pressure Distribution

E. MODEL BASELINE MEASUREMENTS

The model baseline measurements were made using a survey distance of 1.656 inches (equal to the staggered-passage width, Figure 10) with the probe starting position located 0.75 inches above the level of the middle blade trailing edge. ZOC 1 was used for the probe surveys with the measured pressures and their associated ports listed in Table 3. Table 4 lists the probe positions relative to the starting point with point 1 being the beginning of the traverse above the middle blade. Five runs were made to determine the flow profiles and the baseline loss coefficient using the fully-mixed-out conditions calculated as shown in Appendix E. Table 5 lists the tunnel conditions for the five runs and Table 6 lists the results of the fully-mixed-out calculations. Figures 15 through 19 show the blade wake survey results output by the data reduction program "NEW_READ_ZOC1".

TABLE 3. MEASURED PRESSURES AND PORTS ASSIGNED

Measured Pressure psia	Port Assigned
Atmospheric	1
P1	32
P2	24
P3	25
Upstream Static	29
Downstream Static	30
Plenum	31

TABLE 4. PROBE TRAVERSE POSITON

Point	Relative Position-in	Point	Relative Position-in	Point	Relative Position-in
1	0	12	0.50	23	0.84375
2	0.0625	13	0.53125	24	0.875
3	0.125	14	0.5625	25	0.90625
4	0.1875	15	0.59375	26	0.9375
5	0.25	16	0.625	27	0.96875
6	0.3125	17	0.65625	28	1.00
7	0.34375	18	0.6875	29	1.13125
8	0.375	19	0.71875	30	1.2625
9	0.40625	20	0.75	31	1.39375
10	0.4375	21	0.78125	32	1.525
11	0.46875	22	0.8125	33	1.65625

TABLE 5. BASELINE TUNNEL CONDITIONS

Run #	Upstream Static-psia	P2/P1	$T_T(R)$	Plenum-psia	Mass Flux Integral
1	15.279	2.09	518.7	48.45	0.9143
2	15.128	2.08	519.7	47.94	0.9140
3	15.379	2.08	518.2	48.76	0.9196
4	15.043	2.07	518.2	47.75	0.9218
5	15.047	2.09	517.7	47.65	0.9227

TABLE 6. BASELINE FULLY-MIXED-OUT CONDITIONS

Run #	X_3	Pt_3 - psia	β_3-deg	ϖ_{mixed}
1	0.3115	40.73	55.14	0.2328
2	0.3118	40.31	55.15	0.2327
3	0.3100	40.58	54.73	0.2450
4	0.3159	39.76	55.05	0.2443
5	0.3143	39.73	54.92	0.2432
AVERAGE	0.3127	40.22	55.00	0.2396
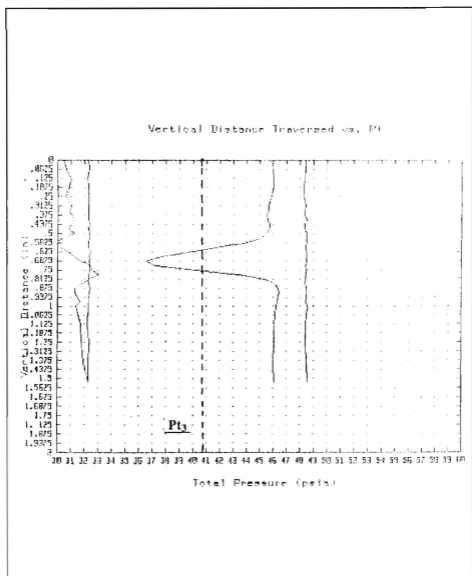
Figure 15. Baseline Blade Wake Survey: Run 1

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Vertical Distance Traversed vs. Pt

Total Pressure (psia)

Pt₃
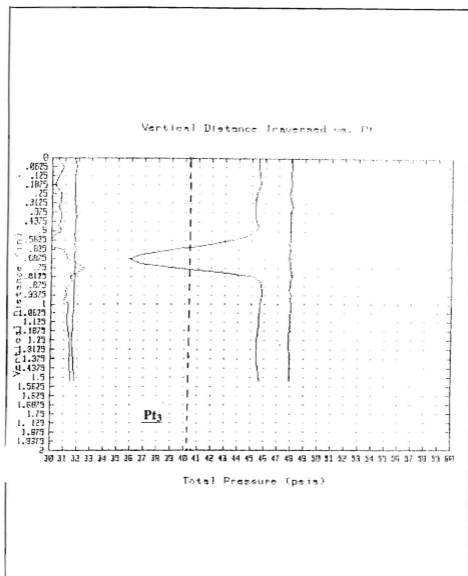
Figure 16. Baseline Blade Wake Survey: Run 2

25
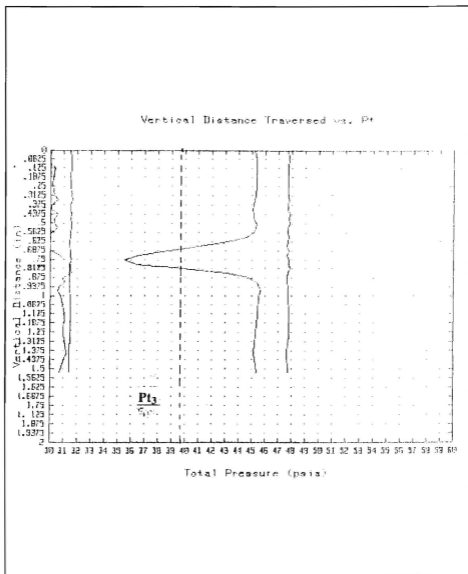
Figure 17. Baseline Blade Wake Survey: Run 3
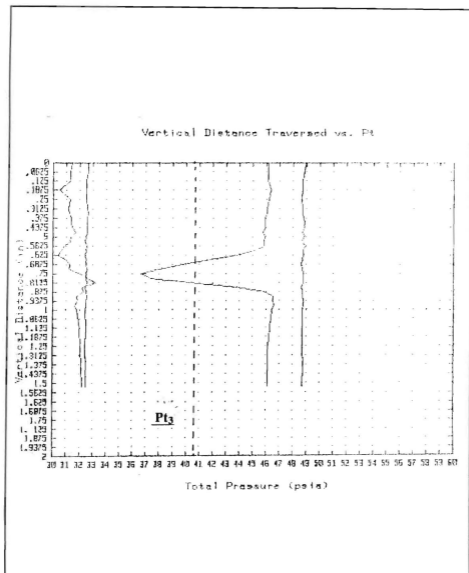
Figure 18. Baseline Blade Wake Survey: Run 4

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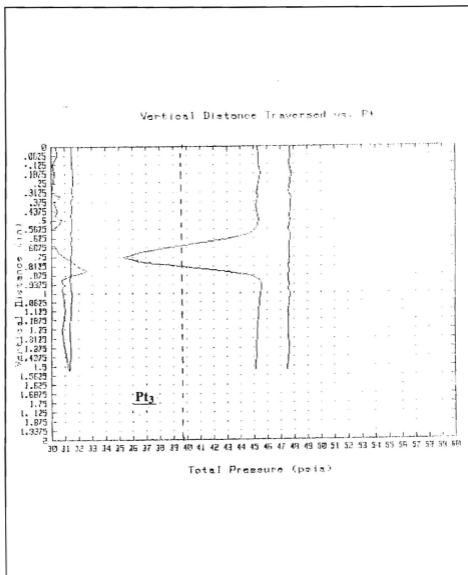
Figure 19. Baseline Blade Wake Survey: Run 5

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In all cases, the calculated fully-mixed-out total pressure (P_{t3}) was repeatable and qualitatively showed a low but not unreasonable value when compared to probe-measured total pressure distribution, which was reasonably periodic. The probe-derived static pressure distributions were also repeatable, and followed the trends of the previously discussed results. The calculated fully-mixed-out loss coefficient was more than twice the mass-averaged loss coefficient as presented in Table 2. The fully-mixed-out calculation subprogram in "NEW_READ_ZOC1" was verified by programming a known test case used by Armstrong [Ref. 12]. It is noted that the test case was at low Mach number, rather than the high subsonic range of the present measurements. However, it is also noted that Armstrong also reported that much higher values were obtained for the fully-mixed-out loss coefficient than for the mass-averaged loss coefficient, when reducing cascade-flow survey data.

IV. CONCLUSIONS AND RECOMMENDATIONS

In the present study, the velocity and flow angle distributions, and the fully-mixed-out losses due to the shock-boundary layer interaction in the transonic fan-blade cascade model, were measured at the design incidence angle. The measured flow field and flow losses provide baseline values for planned measurements with low-profile vortex generator devices installed. The fully-mixed-out loss values were more than twice the mass-averaged loss values reported by Myre [Ref. 5] and Tapp [Ref. 6] and repeated in the present study. The measurements of pressure and flow angle distributions were repeatable. The three-port probe, designed for the present study, gave excellent results in measurements of static pressure, dimensionless velocity and flow angle, at velocities greater than M = 0.4.

The following specific conclusions were drawn:

- Shock placement using the Back Pressure Valve (BPV), Back Pressure Bleed Valve (BPBV), Porous Bleed Valve (PBV), and in-line shadowgraph system was quick, and gave repeatable results.

- The calculated fully-mixed-out flow losses were significantly higher than mass-averaged results. This may have been due to the probe not traversing parallel to the trailing edge, but a more detailed analysis of how this would effect the calculation needs to be made.

- The probe-derived static pressure in the flow from the suction side of the center blade was lower than that from the pressure side, indicating a higher velocity in the upper passage.

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- Angle distributions obtained in the surveys were repeatable and showed less flow turning from the pressure side of the middle blade than from the suction side.

- The probe in its present location, traversing normal to inlet velocity, could not determine the degree of periodicity in the two-passage fan-blade model.

- The probe design had excellent characteristics at medium to high Mach numbers and had the ability to measure accurately in the wake shear layers. Measurements of static pressure and flow angle through the blade wake were consistent with previous experience at lower Mach numbers [Ref. 13].

The following recommendations are made concerning the present pilot and follow-on research program:

- Use the same probe design but increase the range of the angle calibration from -6 degrees to +12 degrees.

- Design and build an apparatus to calibrate the probe in the probe holder while still attached to the motor-controller assembly and utilizing the ZOC system for data acquisition.

- Make more measurements with the current system and validate the calculation of the fully-mixed-out loss .

- Install the 6-5-1 Triangular Plow Vortex Generator Devices and compare the loss measurements and the flow field to the baseline results.

- Once these pilot experiments are complete, proceed *to a* larger apparatus in which Mach number and cascade geometry can be varied. In the larger apparatus, design the traverse to be parallel to the blade trailing edge.

- The larger apparatus should incorporate three blades to improve the ability to simulate periodicity.

APPENDIX A.   PROGRAM "CAL_ACQ"

```
10    !FILE NAME:     CAL_ACQ
20    !DISK LABEL:    CAP.EDU
30    !               C. Patti Austin
40    !LAST MODIFIED 0?/??/??
50    !DESCRIPTION
60    !     THIS PROGRAM ACQUIRES AND REDUCES TRANSDUCER ...
70    !     ...PORT PNEUMATIC PROBE FOR CALIBRATION OF THE PROBE ...
80    !     ...BOTH YAW AND PITCH ANGLE.  THIS PROGRAM ACQUIRES...
90    !     ...THE RAW DATA AT EACH DISCRETE MACH NUMBER AND PITCH ANGLE...
100   !
110   !
120   !     VARIABLES FOR ... FUNCTION
130   !     P  = PRESSURE ...
140   !     PT = YAW ANGLE COUNT
150   !     Q  = SET POINT
160   !     C  = CHANNEL
170   !     DP = DIFF PRESSURE
180   !     ST = SUPPORT SYSTEM CODE
190   !     S  = SQUARE ?
200   !     ...SUBROUTINE INVOKED TO REWARD ONLY
210   !     P1,P2,P3,P4 ... PSTAT
220   !     PRESSURE FROM PROBE (LEFT)
230   !     P2=LEFT PROBE HOLE (FROM DP)   (LEFT)
240   !     P4=RIGHT PROBE HOLE            (RIGHT)
250   !     PSTAT=STATIC PRESSURE
260   !     PTOT=TOTAL PRESSURE
270   !     PAMB=AMBIENT PRESSURE
280   !     G = PITCH SENSITIVE PRESSURE COLLECTED
290   !     B = MACH SENSITIVE PRESSURE COLLECTED
300   !
310   OPTION BASE 1
320   Gamma=1.4
330   CLEAR SCREEN
340   DISP "PLEASE WAIT WHILE RESETTING SOUNDS..."
350   INPUT
360   V=5
370   A=1
380   GOSUB Read
390   !*************************************************
400   PRINT "DATA ACQUISITION FOR CALIBRATION OF ... FIVE HOLE PROBE"
410   DIM V(1,0),A(1,4),H(1,1)
420   DIM P(H,1,72),P2(H,1,72),P3(H,1,72),Pstat(H,1,72),PTOT(H,1,72),...
430   DIM P4(H,1,72),H2(H,1,72),H3(H,1,72),B(H,1,72)
440   DIM PAMB(H,1,72),PSAT(H,1,72)
450   INPUT "ENTER MONTH,DAY,YEAR (i.e. 08,20,91)",...
460   PRINT USING "K,DD,...";MO,"/",DA;"/",... "DATE OF INPUT ...
470   INPUT "ENTER RUN #:",Cnt
480   A$="HD:AVAC$(V(1)):AVAC0.9C(1)):AVAL,REY=(SOUR,REY=?)"
490   B$="HD:AVAC$(V(1)):AVAC0.9C(1)):AVAL,REY=(SOUR,REY=?)"
500   CREATE ASCII A$&";",AVAL,0,1",LR   !CREATES RAW DATA FILE
```

Figure A1.   Program   "CAL_ACQ"

```
...     ...
530   ASSIGN @Path2 TO HP8_1;"09_dat"
540   PRINT
550   PRINT "FOR DATA FILE #DBLE"$DB
560   PRINT
570   PRINT "PLEASED DATA FILE #DBLE"$DB
580   PRINT
590   PRINT   INPUT8_1 TO P_9_9,R_1  PRINT8_1 TO P_9_9,R_1 IN ...  ...
600   PRINT
610   PRINT       SET UP THE (BLB) FOR SCANIVALVE #14 PRESS(00 TO0 = 0.15  ...  ...
620   PRINT
630   PRINT   TO SCANIVALVE PORT #2"
640   PRINT
650   PRINT DATA INP _F00_  FINISH BOTH BENDER AND CLEAR PORT   ...
660   INPUT "ENTER ADDRESS PRESSURE IN LBS ",Info
670   INPUT Ptong[C_00]bytes
680   PRINT
690   PRINT "SET =5 dpg BLEEDER"
710   PRINT
720   PRINT ****PRESS CONTINUE WHEN READY****
730   PAUSE
740   CLEAR SCREEN
750   PRINT
760   FOR Flight=1 TO 15
770        Yes
780        n=1
790        GOSUB Head
800   ***********************************************************
810   !
820   ***********************************************************
830   !RECORD THE PRESSURE DATA FOR THIS PATCH AND ANGLE
840   !
850        OUTPUT 722;"ERROR OM211"        !       SETS UP HP34589 FOR
860        V=5      !SCANIVALVE IS DESIRABLE
870        S=1      !HP34589 SCANNER IS DESIRABLE
880   !
890        PRINTER IS 711
900        PRINT
910        PRINT "Mach = ",Mach
920        PRINT "Pitch angle = ",Pitch
930        PRINT USING "7.5X,3.DDD,7.2X,8.15X,7.17X,8";"SCANIVALVE #",""," ",""
              n[15],"7X1"
940        PRINT
950        PRINTER IS CRT
960   !READ THE SCANIVALVE PORTS
970        FOR n=1 TO n
980            GOSUB Read
990            WAIT 2.0
1000           OUTPUT 701;"C"     ! CLOSES SCANNER #1
1010           OUTPUT 701 USING "#B";"OPEN[SCANNER #1 SET TO READ SCANIVALVE (0)]
1020           OUTPUT 722
1030           ENTER 722;V##
```

Figure A1. (cont)   Program   "CAL_ACQ"

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```
1080  !   -.------ TO PSI
1090      IF A=1 THEN
1080         Patm(Mach_Pitch)=100/1000
1080         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",...,PDD.DDDDD ...
1100      PRINTER IS 701
1110         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",... 700 DDDDD ...
1120      PRINTER IS 701
1130      END IF
1140      IF A=1 THEN
1150         -.-(Mach_Pitch)=100/1000
1160         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",...,PDD.DDDDD ...
1170      PRINTER IS 701
1180         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",... 700 DDDDD ...
1190      PRINTER IS 701
1200      END IF
1210      IF A=1 THEN
1210         Plot(Mach_Pitch)=100/1000)=Patm(Mach_Pitch)/scale
1220         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",... 700 DDDDD (Mach.
1230      PRINTER IS 701
1240         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",... 700 DDDDD (Mach.
1250      PRINTER IS 701
1260      END IF
1270      END IF
1280      IF A=1 THEN
1290         Patm(Mach_Pitch)=100/1000)=Patm(Mach_Pitch)(Am)
1290         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach
Pitch)
1310      PRINTER IS 701
1320         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach
Pitch)
1330      PRINTER IS 701
1340      END IF
1350      IF A=1 THEN
1360         (11(Mach_Pitch)=100/1000)=Patm(Mach_Pitch)(Am)
1370         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
ch)
1380      PRINTER IS 701
1390         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
ch)
1400      PRINTER IS 701
1410      END IF
1420      IF A=1 THEN
1430         (11(Mach_Pitch)=100/1000)=Patm(Mach_Pitch)(Am)
1440         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
ch)
1450      PRINTER IS 701
1460         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
ch)
1470      PRINTER IS 701
1480      END IF
1490      IF A=1 THEN
1500         (11(Mach_Pitch)=100/1000)=Patm(Mach_Pitch)(Am)
1510         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
ch)
1520      PRINTER IS 701
1530         PRINT USING "2X,DDD,2X,7DD.DDDDDDDD",2X,700.DDDDD (2X701 (Mach.Pit
```

Figure A1. (cont) Program "CAL_ACQ"

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```
1450        PRINTER IS  711
1550        P_V(Bach_Pitch)=(1./Bach_Pitch)*(Bch_...........................
1560        B(Bach_Pitch)=(1./Bach_Pitch)=V(Bch_Pitch)........................
      Bach_Pitch)!
1570        P(Bach_Pitch)=P(Bach_Pitch)!  ..(Bach_Pitch...............
1580        =(Bach_Pitch)=Bch(1)-EXP((Ganma-1)=Ganma...............
      P=E(Bch_Pitch)!! !
1590        =E(Bach_Pitch)=SIN(1)=(Ganma-1)=(Bach_Pitch)=... ...(1)=(Pitch)
      ! !!
1600        FDR I]
1610    *****************RAGE OUTPUT.......................................
1620      NEXT B
1630    !!PRINT "Bach = ";(1(Bach_Pitch)
1640      !PRINT "Ganma = ";(1(Bach_Pitch)
1650      !!PRINT "Beta = ";(1(Bach_Pitch)
1660      PRINT DL... !S OFF
1670      PRINT
1680      PRINT "SET NEW FILTER RANGE - PRESS CONTINUE WHEN READY"
1690      PAUSE
1700      PAUSE
1710      CLEAR SCREEN
1720      NEXT Pitch
1730      PRINT "SET NEW MACH NUMBER - PRESS CONTINUE WHEN READY"
1740      PAUSE
1750      PAUSE
1760      CLEAR SCREEN
1770      NEXT Mach
1780      GOTO 1170
1790    !
1800    !************************END OF MAIN PROGRAM*******************
1810    !
1820    !*****SUBROUTINE TO POSITION AND READ THE PROBE**********
1830    !!!!!SUBROUTINE OF HAS TRUE PROBE FEATURE
1840    Newposition: !H2 USING "#,(,()"
1850      Kd=SQRT(J/72)
1860      L=H(RANGE)/(H,150
1870      T!=SQRT(H)*(HR,4)
1880      M!=(H)*(RANGE)!(,7)
1890      P=1**M/L
1900      CLEAR 707
1910      IF J=0 THEN Finish
1920      OUTPUT 701;"C"
1930      OUTPUT 701 USING "DDD";J=J
1940      OUTPUT 701;"C"
1950      WAIT .5
1960      GOTO 1920
1970    Finish:TOWN
1980    !************************************************************
1990        !************************************************
2000        !*****************************SAVE DATA TO DDF0 DATA*******
2010        !*******************************DATA SAVED TO ";,700,0(,!*******
2000    OUTPUT 8;Kd=Kb=B
2020    OUTPUT 8;Pitch=B=B
2030    OUTPUT 8;Kd=b(1=Beta(*),P=n(*),B=t(*)=)!Runt=..(1)(1)!(*)!(*)!
2040    OUTPUT 8;
2050    PRINTER IS  CRT
2060    END
```

Figure A1. (cont) Program "CAL_ACQ"

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APPENDIX B. PROBE CALIBRATION RAW DATA

TABLE B1. PROBE CALIBRATION RAW DATA   X = 0.10 - 0.22

ANGLE (deg)	Pt (psia)	P2 (psia)	P3 (psia)	PSTAT(psia)	PTOT(psia)	P2 & P3 avg	X	GAMMA	BETA
-5	15.4089	15.1831	15.2424	14.8421	15.3841	15.21275	0.1030245	-0.30543394	0.0126015
-4	15.4051	15.201	15.2288	14.8217	15.359	15.2139	0.10473862	-0.13433724	0.0224147
-3	15.412	15.2172	15.228	14.8271	15.365	15.2226	0.10448925	-0.05702218	0.0228913
-2	15.413	15.2133	15.2176	14.83	15.3644	15.21545	0.10442152	-0.02176664	0.0128171
-1	15.4092	15.2139	15.212	14.8278	15.3684	15.21295	0.10453122	0.00968153	0.0127359
0	15.4059	15.24	15.2029	14.8277	15.3615	15.22145	0.1045061	0.13602841	0.01118181
1	15.422	15.2527	15.1931	14.8292	15.3692	15.2229	0.10424477	0.20072327	0.01199834
2	15.4132	15.2574	15.174	14.8223	15.3688	15.2157	0.10559906	0.29334706	0.01291013
3	15.4128	15.2509	15.1687	14.8258	15.3484	15.2098	0.10503718	0.42227848	0.01291369
4	15.4117	15.2603	15.1581	14.8222	15.3711	15.2092	0.10499581	0.50469136	0.01317907
5	15.4224	15.2587	15.141	14.8241	15.359	15.19985	0.1080242	0.52866592	0.01443031
-5	15.8937	15.4876	15.592	14.8261	15.8155	15.5398	0.14025733	0.29499855	0.0222568
-4	15.9035	15.5064	15.5772	14.8272	15.8343	15.5418	0.14027903	0.19574233	0.0274342
-3	15.8948	15.528	15.5528	14.8302	15.8378	15.5486	0.14012025	0.11907514	0.0278834
-2	15.8884	15.5387	15.5504	14.8383	15.8079	15.54455	0.13922858	0.03402647	0.0218417
-1	15.9001	15.5826	15.544	14.8282	15.8159	15.5533	0.14051896	0.05363322	0.0218118
0	15.9038	15.5784	15.5248	14.8319	15.8189	15.5505	0.1404959	0.14651781	0.0221482
1	15.8893	15.5801	15.5177	14.8373	15.8085	15.5489	0.13929737	0.18331375	0.02142322
2	15.8949	15.5785	15.4869	14.842	15.8186	15.5327	0.13925374	0.25289895	0.02278718
3	15.902	15.6135	15.4591	14.8454	15.8082	15.5363	0.13947239	0.42220399	0.02278718
4	15.9012	15.6104	15.4453	14.8434	15.8202	15.52785	0.13955715	0.44721224	0.02347936
5	15.8893	15.624	15.4178	14.8423	15.8314	15.5209	0.13887839	0.5597177	0.0231854
6	15.9048	15.6245	15.4049	14.8523	15.8531	15.5147	0.13918855	0.56322134	0.0245149
-5	16.7033	15.9884	16.1263	14.8523	16.5731	18.07435	0.18166117	-0.27967247	0.0376542
-4	16.7008	16.0075	16.1363	14.8478	16.6051	16.07195	0.18175352	-0.20472441	0.0376423
-3	16.7146	16.0353	16.1104	14.8482	16.5912	16.07285	0.18238385	-0.11702376	0.0383945
-2	16.888	16.084	16.1058	14.852	16.5869	16.0949	0.18097829	-0.06930857	0.0361394
-1	16.6889	16.0893	16.0517	14.8503	16.5856	16.0705	0.18110681	0.08080207	0.0370545
0	16.6923	16.1223	16.0417	14.8521	16.5606	16.082	0.18098687	0.13253749	0.0383084
1	16.6791	16.1497	16.0074	14.8482	16.5721	16.07855	0.18076623	0.23594848	0.0360614
2	16.6949	16.1683	15.9498	14.8534	16.584	16.05855	0.18122717	0.33995446	0.0381483
3	16.6901	16.181	15.9271	14.8331	16.5367	16.0541	0.18102295	0.39937107	0.0381062
4	16.6866	16.201	15.8837	14.8537	16.5511	16.03985	0.18082679	0.49882027	0.0387708
5	16.7041	16.2095	15.863	14.8527	16.5727	16.03625	0.18184127	0.51882908	0.03980012
6	16.7016	16.2124	15.8461	14.8582	16.5726	16.02925	0.18128133	0.5544053	0.04025582
-5	17.8676	16.6035	16.8234	14.8805	17.4969	16.71195	0.29488904	-0.22846308	0.05516011
-4	17.882	16.8495	16.8131	14.8781	17.5306	16.7313	0.21993068	-0.17578167	0.05269505
-3	17.8364	16.8728	16.7724	14.8804	17.5167	16.7226	0.21252902	-0.1089954	0.0518133
-2	17.8874	16.7212	16.8946	14.8837	17.4937	16.8079	0.21847432	0.02751772	0.05537391
-1	17.8858	16.742	16.8751	14.8864	17.4886	16.70855	0.22031339	0.06845741	0.05532519
0	17.8647	16.8046	16.8248	14.8988	17.4614	16.7148	0.21925774	0.18943363	0.05451115
1	17.8649	16.8319	16.5729	14.8734	17.5813	16.6949	0.21911454	0.29247423	0.05491115
2	17.8653	16.8582	16.5351	14.8728	17.5326	16.66715	0.22972855	0.32784664	0.0558747
3	17.8804	16.8803	16.4737	14.8707	17.4924	16.532	0.21911539	0.47883554	0.0567438
4	17.8673	16.9044	16.4341	14.8748	17.5138	16.6469	0.22186422	0.52578442	0.0572491
5	17.8549	18.9102	16.379	14.8718	17.5138	18.6446	0.21870422	0.52578442	0.05722491
6	17.659	18.9328	16.3267	14.875	17.5236	15.82975	0.21671483	0.58887539	0.05802473

TABLE B2.   PROBE CALIBRATION RAW DATA   X = 0.26 - 0.37

ANGLE (deg)	P1 (psia)	P2 (psia)	P3 (psia)	PSTAT(psia)	PTOT(psia)	P2 & P3 avg	X	GAMMA	BETA
-5	19.2303	17.8324	17.9378	14.9019	19.0151	17.785105	0.26507724	-0.21132788	0.07515197
-4	19.2236	17.8813	17.88121	14.8894	19.0381	17.781253	0.26532298	-0.13860088	0.07502981
-3	19.2013	17.7207	17.82441	14.8889	18.9791	17.772555	0.28475814	-0.07259818	0.07440878
-2	19.2342	17.7831	17.78881	14.8911	18.96	17.788455	0.26554165	-0.00463479	0.07526931
-1	19.2042	17.83	17.69861	14.8931	18.9864	17.764305	0.26459236	0.09124971	0.07497813
0	19.2137	17.9099	17.63951	14.8948	18.9402	17.774705	0.26489897	0.18780197	0.07469422
1	19.221	17.9582	17.57981	14.8948	19.0225	17.769005	0.26507365	0.26060007	0.07554212
2	19.2201	17.9927	17.50731	14.9019	18.919	17.750005	0.28481125	0.33017594	0.07648739
3	19.2022	18.0347	17.43571	14.9005	18.9382	17.735705	0.28439006	0.42758818	0.0763712
4	19.2302	18.0481	17.34001	14.8887	18.9358	17.694055	0.28518222	0.46095258	0.0798819
5	19.233	18.1032	17.29101	14.9018	19.0197	17.697105	0.28515766	0.52880588	0.07985729
6	19.2483	18.115	17.22141	14.9034	18.9288	17.668205	0.28544324	0.56824801	0.08199472
-5	20.7578	18.889	19.0576	14.9191	20.5555	18.6633	0.30008337	-0.20512088	0.0912665
-4	20.7889	18.7415	19.0014	14.9198	20.5097	18.71145	0.3007079	-0.1355446	0.09223432
-3	20.7824	18.5849	18.9214	14.9235	20.5139	18.67825	0.3004484	-0.04553213	0.0916232
-2	20.7885	18.9026	18.8654	14.9229	20.5158	18.884	0.30081477	0.01953166	0.09161752
-1	20.7828	18.8754	18.7987	14.9318	20.5023	18.88805	0.30023813	0.09421378	0.09128537
0	20.8028	19.0234	18.7096	14.936	20.5472	18.8665	0.3053062	0.16208166	0.09307882
1	20.7701	19.0977	18.6358	14.9234	20.5548	18.86675	0.30021511	0.24267738	0.09143894
2	20.7921	19.134	18.539	14.9278	20.5648	18.838	0.30055141	0.3046879	0.094079
3	20.7837	19.1791	18.4288	14.941	20.41	18.80385	0.29957054	0.38293747	0.09438828
4	20.7887	19.2317	18.3189	14.9352	20.5148	18.7753	0.30026045	0.45338247	0.09865099
5	20.7878	19.251	18.2592	14.9303	20.5365	18.7551	0.2999869	0.4927709	0.09661445
6	20.7458	19.2889	18.1407	14.9357	20.4787	18.7148	0.29935007	0.56533727	0.09789933
-5	22.9359	20.299	20.7481	15.009	22.4401	20.52355	0.33781229	-0.18606968	0.10521992
-4	22.9201	20.3708	20.6378	14.9989	22.5759	20.5043	0.33783994	-0.11052239	0.10540094
-3	22.923	20.4329	20.5426	15.0086	22.6422	20.48775	0.33764505	-0.04504871	0.10823609
-2	22.9085	20.5355	20.4681	15.003	22.5493	20.5008	0.33745501	0.03328168	0.10502259
-1	22.9412	20.8033	20.3866	15.0114	22.8714	20.44495	0.33782262	0.09836641	0.1070672
0	22.9368	20.6818	20.257	15.008	22.4892	20.4692	0.33780882	0.16326531	0.10808761
1	22.9355	20.7736	20.1675	15.0055	22.8154	20.47055	0.33787852	0.24580729	0.10746535
2	22.9871	20.8813	20.0901	15.005	22.4924	20.4857	0.33840443	0.30954483	0.10847691
3	22.9706	20.9014	19.9547	14.9887	22.6625	20.42805	0.33881829	0.37234275	0.11068714
4	22.9307	20.9408	19.8011	15.0055	22.6417	20.37085	0.33773839	0.44514327	0.11163418
5	22.9279	20.9603	19.7244	15.0059	22.5477	20.34245	0.33778375	0.47764385	0.11278436
6	22.9097	21.0078	19.8158	15.0087	22.517	20.3133	0.3373749	0.53476115	0.11333191
-5	25.185	21.9479	22.461	15.0729	24.9006	22.20445	0.36935398	-0.17214944	0.11834624
-4	25.1712	22.0445	22.3655	15.0751	24.8853	22.207	0.36912206	-0.10694285	0.11778157
-3	25.2068	22.1735	22.2919	15.0745	24.8858	22.2337	0.36960872	-0.03980902	0.1178915
-2	25.1828	22.2658	22.2165	15.0789	25.0103	22.24115	0.36962361	0.016753	0.11681187
-1	25.2425	22.5807	22.0764	15.0788	24.9345	22.32855	0.37002847	0.10059305	0.11939982
0	25.23568	22.4609	21.9726	15.0715	24.994	22.21675	0.37005558	0.18174605	0.11952943
1	25.2549	22.6099	21.9043	15.0724	24.9446	22.2571	0.37033665	0.23537261	0.11870172
2	25.2329	22.8284	21.7488	15.0771	24.87	22.288	0.36989506	0.28936562	0.12053219
3	25.2277	22.8878	21.5981	15.0747	25.0085	22.24295	0.36987942	0.35317763	0.12228027
4	25.2992	22.8057	21.4402	15.0883	25.0401	22.12295	0.37052159	0.42990948	0.12554745
5	25.2022	22.8202	21.3164	15.0737	24.8398	22.0683	0.3695642	0.47694939	0.12435026
6	25.278	22.9017	21.2615	15.0831	24.7932	22.0816	0.37033101	0.51346106	0.12538375

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APPENDIX C. APPLICATION OF THE CALIBRATION
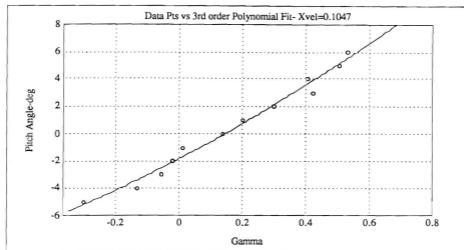
Figure C1.   Pitch Angle vs. Gamma   X = 0.1047
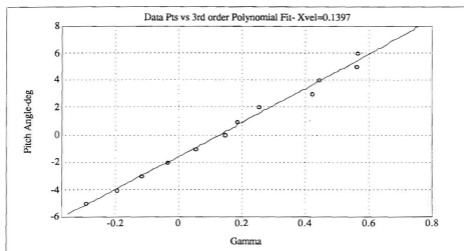
Figure C2.   Pitch Angle vs. Gamma   X = 0.1397
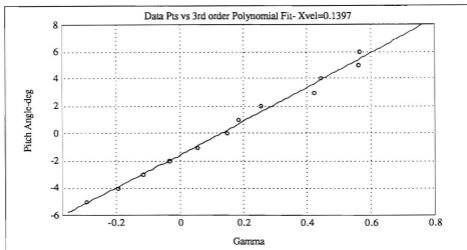
Figure C3. Pitch Angle vs. Gamma   X = 0.1812
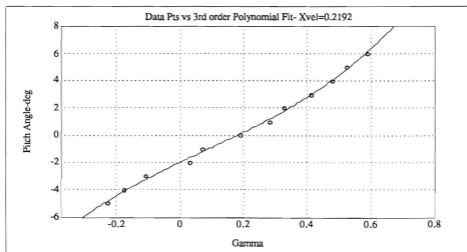
Figure C4. Pitch Angle vs. Gamma   X = 0.2192
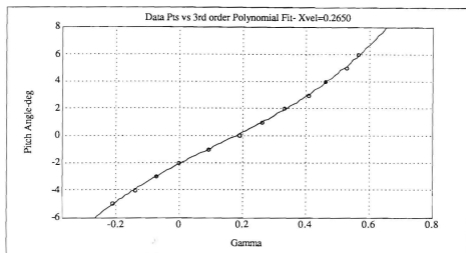
Figure C5. Pitch Angle vs. Gamma   X = 0.2650
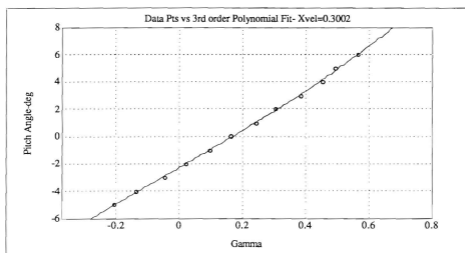
Figure C6. Pitch Angle vs. Gamma   X = 0.3002
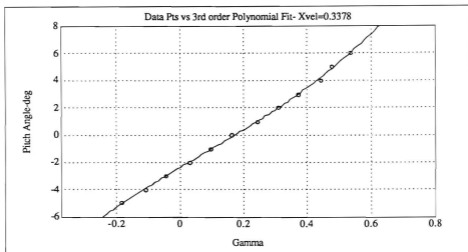
Figure C7.   Pitch Angle vs. Gamma   X = 0.3378
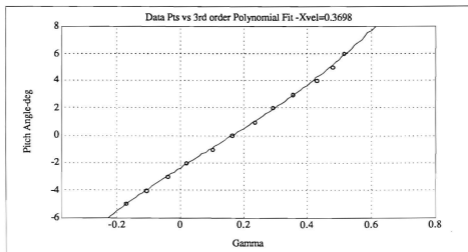
Figure C8.   Pitch Angle vs. Gamma   X = 0.3698
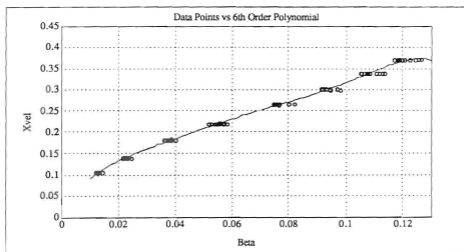
Figure C9. X vs. Beta

TABLE C1.   **CALIBRATION METHOD RESULTS   X = 0.10 - 0.22**

ANGLE (deg)	ACTUAL X	CALIBRATED X	CALIBRATED ANGLE	Angle Difference	X % Difference
-5	0.10302443	0.10457949	-5.271	0.271	1.50940746
-4	0.10473655	0.10371192	-3.4375	0.5625	0.97829573
-3	0.10484919	0.10314849	-2.529	0.471	1.62203994
-2	0.10487293	0.10555298	-2.103	0.103	0.84075906
-1	0.10453115	0.10518767	-1.716	0.716	0.62805825
0	0.10450603	0.10124488	-0.109	0.109	3.12053738
1	0.1042947	0.10179391	0.759	0.241	2.39780855
2	0.10553013	0.10596948	2.15	0.15	0.41632236
3	0.10538899	0.10553766	3.93	0.93	0.14107116
4	0.10503711	0.10712581	3.678	0.322	1.98853771
5	0.10499554	0.10698696	5.167	0.167	1.89667253
6	0.10602413	0.11249207	5.517	0.483	6.10044264
-5	0.14025224	0.13980665	-5.09	0.09	0.31770656
-4	0.14079258	0.14122875	-3.91	0.09	0.30979645
-3	0.14012016	0.1382986	-3.01	0.01	1.29999554
-2	0.13922859	0.13791107	-1.988	0.012	0.94630291
-1	0.14051257	0.13841175	-0.919	0.081	1.49511339
0	0.14049581	0.13965073	0.2365	0.2365	0.60149886
1	0.13921777	0.13724023	0.6768	0.3232	1.42046589
2	0.13925365	0.13925365	1.5324	0.4676	2.5998E-06
3	0.1394723	0.1419776	3.647	0.647	1.7962704
4	0.13955706	0.1433869	3.902	0.098	2.74428123
5	0.1388783	0.1443133	5.265	0.265	3.9134965
6	0.13916946	0.14635418	5.55	0.45	5.16257237
-5	0.18166106	0.18007618	-5.124	0.124	0.87243932
-4	0.18176341	0.1800474	-3.92	0.08	0.94408982
-3	0.18238375	0.1818689	-2.749	0.251	0.28338434
-2	0.18097817	0.17639308	-2.231	0.231	2.53350638
-1	0.1811067	0.17862118	-0.8679	0.1321	1.37240608
0	0.18009676	0.1768594	-0.1500	0.1508	2.28047625
1	0.18076612	0.17609679	0.9432	0.0568	2.5996715
2	0.18122165	0.18126723	2.077	0.077	0.02514951
3	0.18102283	0.18117063	2.913	0.087	0.08164354
4	0.18082666	0.18277423	4.608	0.608	1.07703754
5	0.18164116	0.18568528	4.997	0.003	2.22643459
6	0.18128121	0.18634556	5.535	0.465	2.79364135
-5	0.2194901	0.22083929	-4.858	0.142	0.61469162
-4	0.21869114	0.21533631	-4.038	0.038	1.53405034
-3	0.21852929	0.21334476	-3.145	0.145	2.37246331
-2	0.21941948	0.2189379	-1.666	0.334	0.21948013
-1	0.22001366	0.22098927	-1.215	0.215	0.44343307
0	0.219258	0.21775675	0.1151	0.1151	0.68469612
1	0.2191148	0.22028799	1.2	0.2	0.53542175
2	0.21973005	0.22241454	1.789	0.211	1.22172576
3	0.21999565	0.22488684	3.007	0.007	2.22331157
4	0.21911565	0.22438852	4.066	0.066	2.40643095
5	0.21870449	0.22530943	4.899	0.101	3.0200314
6	0.21867328	0.22766856	6.191	0.191	4.11356991

TABLE C2.   CALIBRATION METHOD RESULTS   X = 0.26 - 0.37

ANGLE (deg)	ACTUAL X	CALIBRATED X	CALIBRATED ANGLE	Angle Difference	X % Difference
-5	0.26507717	0.2619759	-5.013	0.013	1.1699502
-4	0.26532291	0.26177636	-3.889	0.111	1.35176715
-3	0.26475806	0.26051754	-2.977	0.023	1.60165967
-2	0.26554158	0.26220818	-2.125	0.125	1.52607285
-1	0.26469231	0.26163475	-0.9976	0.0024	1.15513717
0	0.2648899	0.26147008	0.1185	0.1185	1.29103287
1	0.26507358	0.26274165	0.99788	0.00212	0.87572867
2	0.26481118	0.26459853	1.908	0.092	0.08030137
3	0.26439052	0.26437015	3.039	0.039	0.00770505
4	0.26518215	0.27131254	3.981	0.019	2.31176687
5	0.26515759	0.27126343	5.206	0.206	2.30272106
6	0.26544316	0.27555841	5.9705	0.0295	3.81070088
-5	0.30008337	0.29543526	-4.997	0.003	1.54894039
-4	0.3007079	0.29766971	-4.053	0.053	1.01034686
-3	0.3004684	0.29625409	-2.846	0.154	1.40258162
-2	0.30061477	0.298241	-1.9896	0.0104	1.45494093
-1	0.30023613	0.29543177	-1.004	0.004	1.60019508
0	0.30053062	0.29964959	-0.091	0.091	0.29315864
1	0.30021511	0.29629037	1.001	0.001	1.30730965
2	0.30055141	0.3020306	1.921	0.079	0.49215954
3	0.29957054	0.30277494	3.09	0.09	1.06966512
4	0.30026045	0.30883693	4.23	0.23	2.85634722
5	0.2999669	0.30899709	4.889	0.111	3.0103945
6	0.29935007	0.31149122	6.2	0.2	4.05583392
-5	0.33781195	0.33103523	-5.013	0.013	2.00606283
-4	0.33783959	0.33154321	-3.888	0.112	1.86372124
-3	0.33764471	0.33385295	-2.965	0.035	1.12300352
-2	0.33734466	0.33049924	-1.944	0.056	2.06404389
-1	0.33782227	0.3381555	-1.037	0.037	0.49338794
0	0.33786794	0.33898174	-0.123	0.123	0.32965667
1	0.33787817	0.33725878	1.039	0.039	0.18331802
2	0.3384048	0.34005809	1.998	0.002	0.48876627
3	0.33861794	0.34611675	3.037	0.037	2.21453438
4	0.33179804	0.3486671	4.32	0.32	3.21762102
5	0.33786715	0.35165497	4.95	0.05	4.08084063
6	0.33734566	0.35312697	6.103	0.103	4.66911618
-5	0.36936742	0.36484632	-4.995	0.005	1.22401028
-4	0.36912224	0.36361324	-3.942	0.058	1.49245984
-3	0.3696089	0.36409248	-2.931	0.069	1.49250252
-2	0.36923632	0.36155338	-2.114	0.114	2.08076611
-1	0.37002864	0.36684095	-0.9156	0.0844	0.86147213
0	0.3700547	0.36725098	-0.0529	0.0529	0.75765544
1	0.37028942	0.36552042	1.007	0.007	1.28791266
2	0.36989523	0.36894868	1.839	0.161	0.25634167
3	0.3698796	0.37124174	2.87	0.13	0.36826666
4	0.37052177	0.37356432	3.209	0.209	0.82115315
5	0.36956438	0.3731039	5.1418	0.1418	0.95775437
6	0.37034436	0.37357425	5.808	0.192	0.87213134

APPENDIX D. PROGRAM "NEW_READ_ZOC1"

```
10   ! Program: NEW_READ_ZOC1
20   ! Description: Reads specified data compiled from program NEW_ZOC_ZOC.
30   ! by Piet Wedding
40   ! modified by David Muir
50   ! modified 5 Nov 1992
51   ! modified 24 Feb 1993 by Jeff Austin for ...  parcel computation ... ...
52   ! to determine dimensionless velocity and deviations onto during ... spike
53   ! traverse.  Program will also determine losses calculated from ...  ...
54   ! spike.
60   !**********************************************************************
70   CLEAR SCREEN
80   PRINTER IS CRT
90   !Variable definition and dimension
100  COM /Print_labels/ PRD$_no_xf,Yo_xf,Dv_dh,Titl+Fl$Fl_!Label$F$Fl_1 label$
601  !
110  INTEGER Disk_drive,Zoc_num,Max_Sample,num_Sample,mo_Pos,col
120  INTEGER Cnt1,mo,Scan_no,avg
130  DIM T_lb$[80]
140  !Tim table initialization
150  P_atm=13.696         !Standard day atmospheric pressure
160  Cnv=.4413353         !Conversion from in Hg to psi
170  Length1_A            !Ratio of specific heats
180  Tsc=0075             !Sub square string
190  a=1=sated=0
200  !Dimension string variable for data location:
210  DIM Data_disc1$[23]
220  DIM Data_disc2$[23]
230  !
240  !**********************************************************************
250  !HOT KEY ROUTINES AND INITIAL SCREEN DISPLAY
260  !**********************************************************************
270  !
280  ON KEY 1 LABEL "ZOC     INPUT   " GOTO Input
300  ON KEY 3 LABEL "PRINT   DATA    " GOTO Print
320  ON KEY 5 LABEL "Pl      "        GOTO Plot
330  ON KEY 6 LABEL " "               GOTO Hold
340  ON KEY 7 LABEL " "               GOTO Hold
350  ON KEY 8 LABEL "EXIT    FROG    " GOTO Finish
360  !
370  !**********************************************************************
380  !INITIAL SCREEN DISPLAY
390  !**********************************************************************
400  !
410 Reset: !
420          CLEAR SCREEN
430  PRINT
440  PRINT
450  PRINT "     READ ZOC DATA AND DISPLAY AS SHOWN"
460  PRINT
470  PRINT "     Input ZOC information and read data           (1)"
490  PRINT "     Print data to CRT or PRINTER                  (3)"
500  PRINT "     Plot Fl data/Print losses                     (5)"
511  PRINT "     Print out xxxl and Deviation angle"
512  PRINT "     vs Vertical Distance Down until READ SCREEN"
520  PRINT "     Determines fully mixed out loss coefficient,"
530  PRINT
540  PRINT "     Exit Program                                  (8)"
560  PRINT
560  !
570 Hold: !
580          GOTO Hold
```

Figure D1. Program "NEW_READ_ZOC1"

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```
1720  !
1290  Print!   !Reads reduced data to array.
1295      !
1300  Sample_min=1              ! First sample
1310  Sample_max=Sample_number  ! Last sample
1320      !
1330  FOR Scan=1 TO Scan_max
1340      !
1350      FOR Port_number=1 TO 32
1360          !
1370          Iu_sum=0
1390          FOR Sample=Sample_min TO Sample_max
1390              Pu=Data(Sample,Port_number)   ! Data point for channel (I)
1400              Iu_sum=Iu_sum+Pu
1410          NEXT Sample
1420          !
1430          Iu_avg=Iu_sum/Sample_number  !*Sum IP data
1440          Pu(Port_number,Scan)=Iu_avg
1450      !
1460      NEXT Port_number
1470      Sample_min=Sample_min+Sample_number
1480      Sample_max=Sample_max+Sample_number
1490      !
1500  NEXT Scan
1510  DISP "Data read from disk and transferred to array."
1520  WAIT 2
1530  GOTO Reset
1540  !*******************************************************
1590  !PRINTS DATA TO PRINTER OR CRT SCREEN AS DESIRED
1620  !*******************************************************
1830  !
1840  Print!!
1850      CLEAR SCREEN
1860      !
1870  INPUT "Print results to screen or printer (0=Screen 1=Printer)",Prin
1880  IF Prin=1 THEN PRINTER IS 702
1890      !
1900      !
1910  PRINT "Data Print Out for Zoc #";Zoct", Run #";Run;", File:";Data_file$
1920  PRINT TAB(5);"Period between samples (sec):";Period
1930  PRINT TAB(5);"Sample collection rate (Hz):";Rate
1940  PRINT TAB(5);"Number of samples per port:";Sample_number
1950  PRINT TAB(5);"Length of data run (sec):";Period*3+Sample_number+Scan_max
1960  PRINT TAB(5);"The scan type is:";Scan_type
1970  PRINT TAB(5);"Number of scans/traverses:";Scan_max
1980  PRINT TAB(5);"Increment of traverse:";Increment;" inches"
1990  PRINT TAB(5);"Atmospheric pressure is:";Pf_atm;" psia"
2000  PRINT TAB(5);"Tunnel Pressure Ratio is:";Pt+Pt(20,1)"/Pa(20,1)
2010  PRINT!
2020  PRINT!
2030      !
2040  Format1!  IMAGE 2D,6X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D
,2D,3D
2050  Format2!  IMAGE 2D,5X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D,4X,2D,3D
,2D,3D
2060      !
2070  IF Scan_max>7 THEN
2260      PRINT "Scan";",";"          Port Number"
2270      PRINT " ","01","24","25","28","30","31","32"
2280      PRINT!
2290  FOR I=1 TO Scan_max
2300      PRINT USING Format1;Pa(I,I),Pa(24,I),Pa(25,I),Pa(28,I),Pa(30,I),Pa(31
1,I),Pa(32,I)
2310  NEXT I
```

Figure D1. (cont)   Program   "NEW_READ_ZOC1"

47

```
2740  ...
2742  PRINT
2745  DISPLAY
2500  '
2510  DISP
2520  '
2532     PRINT "Port","         Scan Number "
2540     PRINT " ","1","2","3","4","5","6","7",...
2555  '
2560     FOR I=1 TO 32
2570        PRINT USING Format;Port_ll(I),Scan(I),...
2575  '
2580  Format ...
2590     IMAGE ...
2591     ...IF
2604     PRINT IS CRT
2610     DISP Popup
2620  '
2630  '
2640 !********************************************************
2440 !********************************************************
4450 !INPUT ROW DATA OBTAINED INTO ARRAYS TO SAVE AS DISK FILE
4460 !********************************************************
4520  '
4400  '
4590  '
4600  CLEAR SCREEN
4610  '
4520  PRINT "        POST PROCESSING OF TOTAL PRESSURE DATA
4530  PRINT
4540  PRINT
4560  PRINT "     This routine will plot vertical position vs. P1 (rms)"
4560  PRINT "     the probe impact pressure and integrate lesses normalize"
4570  PRINT "     by inlet dynamic pressure to calculate a loss coefficient."
4571  PRINT "     Calculates and prints to think-jet the calculated ... and"
4572  PRINT "     deviation angle and uses this information to calculate a"
4575  PRINT "     fully mixed out loss coefficient.
4590  PRINT
4590  PRINT
4620  INPUT "     Dump plots to laser or think-jet (0:LJ 1:tjet ):",Dump
4630  PRINT "     Type F2 to continuing other inputs necessary later!"
4640  PAUSE
4650  '
4560  IF Dump=1 THEN
4570        DUMP DEVICE IS 8
4560  ELSE
4590        DUMP DEVICE IS 703
4700  END IF
4710  '
4720  !Allocate all real variables
4730  '
4730  ALLOCATE INTEGER Pos2(1:Scan_max)
4750  ALLOCATE REAL P_ref(1:Scan_max)
4750  ALLOCATE REAL P_ref(1:Scan_max)
4770  ALLOCATE REAL P_exit(1:Scan_max)
4790  ALLOCATE REAL Y(1:Scan_max)
4790  ALLOCATE REAL P(1:Scan_max)
4900  ALLOCATE REAL M_inf(1:Scan_max)
4910  ALLOCATE REAL M_exit(1:Scan_max)
4920  ALLOCATE REAL Ma1(1:Scan_max)
4930  ALLOCATE REAL Ma2(1:Scan_max)
4940  ALLOCATE REAL Ma3(1:Scan_max)
4950  ALLOCATE REAL Ma4(1:Scan_max)
4960  ALLOCATE REAL Q(1:Scan_max)
4961  '
4962  !Begin editing of main program to determine X (s) and deviation angle
4963  !Define new variables.
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

48

```
600     ...
610     !OPEN DAT INFORMATION
620     !....................................
630     !
640     ! Input:  !
650     !         !
660     !         !( Allocated) OPEN GOSUB Deallocate.
670     !         !
680     !         !TYPE SPACES
690     INPUT "Enter Doc # (1,2,3), date EX88):",cnt$    !     ...
700     PRINT
710     PRINT
720     PRINT
730     PRINT "Enter the disk drive where data is stored, below."
740     PRINT "       0 = HP internal or 700,0"
750     PRINT "       1 = HP floppy or 700,1"
760     PRINT
770     INPUT "Enter Disk where data is located: Disk drive"
780     INPUT !
790     !
800     !....................................
810     !CREATE/OPEN DATA ASSIGNED
820     !....................................
830     !
840     Data_file1$="ZDC$D#N$"&cnt$&"Ldata"&$ANN_5(Dnn)
850     Data_file2$="ZDD$D#N$"&cnt$&"Ldata"&$ANN_5(Dnn)
860     SELECT Dsk_drive
870     CASE 0
880     Data_disc1$=Data_file1$&":,700,0"
890     Data_disc2$=Data_file2$&":,700,0"
900     CASE 1
910     Data_disc1$=Data_file1$&":,700,1"
920     Data_disc2$=Data_file2$&":,700,1"
930     END SELECT
940     ASSIGN @Data_path1 TO Data_disc1$
950     ASSIGN @Data_path2 TO Data_disc2$
960     !
970     !....................................
980     !DETERMINE NUMBER OF RECORDS AND ENTER DATA.
990     !....................................
1000    !
1010    STATUS @Data_path1,3;N1     ! Determine number of records
1020    STATUS @Data_path2,3;N2     ! Determine number of records
1030    ALLOCATE REAL Cal(N1_1,1)   ! Define REAL array of records
1040    ENTER @Data_path1;Cal(*)
1050    Period=Cal(0,0)
1060    R=1!(Period
1070    Sample_number=Cal(0,1)
1080    Zero=Cal(0,2)
1090    Scan_time=Cal(0,1)
1100    Scan_max=Cal(1,1)
1110    Increment=Cal(2,1)*.FORM274:  !Numeric steps to convert
1120    T_min=Cal(3,1)
1130    !
1140    ALLOCATE REAL Data(1:N2,0:23)  !Allocate real data array
1150    ENTER @Data_path2;Data(*)
1160    IF Scan_max=0 THEN
1170    ALLOCATE REAL Fa(1:23,1:1)
1180    ELSE
1190    ALLOCATE REAL Fa(1:23,1:Scan_max)
1200    END IF
1210    !
1220    Allocated=1     ! Allows deallocation of paths.
1230    !
1240    !....................................
1250    !CREATE AVERAGE OF ALL SAMPLES TO ARRAYS
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

49

```
1750 ALLOCATE REAL P2_15(1..
4854 ALLOCATE REAL P3_rc(1:Scan_max)
4860 ALLOCATE REAL P_at_pl(1:Scan_max)
4868 ALLOCATE REAL P_hi(1:Scan_max)
4869 ! P1 IS P1 in the current probe.
4870 INTEGER N_pts,I,K,Rev                          !Used in Language Interpretation
4871 !! p1=p31
4872 ALLOCATE REAL P2SI(1:Scan_max)
4877 ALLOCATE REAL Beta_p(1:Scan_max)
4877 ALLOCATE REAL Scans_p(1:Scan_max)
4877 ALLOCATE REAL X_ vel(1:Scan_max)
4877 ALLOCATE REAL Total_p(1:Scan_max)
4870 ALLOCATE REAL Pitch(1:Scan_max)
4877 ALLOCATE REAL Y_ (1:Scan_max)
4870 ALLOCATE REAL X_ (integ)(1:Scan_max)
4885 ALLOCATE REAL P_ (integ)(1:Scan_max)
4885 ALLOCATE REAL Phi_1(1:Scan_max)
4884 ALLOCATE REAL Phi_2(1:Scan_max)
4885 ALLOCATE REAL Phi_3(1:Scan_max)
4887 ALLOCATE REAL Phi_4(1:Scan_max)
4880 ALLOCATE REAL Phi_5(1:Scan_max)
4885 ALLOCATE REAL P_D(1:Scan_max)
4890 !
4891 !************************
4892 !
4893 !int pltt
4894           !
4900 !initialize plot parameters
4910 LINE TYPE 1
4920 Title$="Vertical Distance Traversal vs. P?"
4930 X_label$="Total Pressure (psia)"
4940 Y_label$="Vertical Distance (in)"
4860 Ys=38
4860 Xf=68
4970 Y=63
4980 Yf=0
4990 U=20
5000 By=32
5010 MAX Pen2= (-1)
5020 Fen2(1)=-2
5030 Fon2(Scan_max)=-2
5040 !
5050 CALL Plot                       !Sets up graphics environment
5060 !
5070 !Flag quantities calculated and total pressure plotted.
5080 !
5090 G=32.2
5100 Roan=53.7
5110 !                                            !.
5120 ! Read in data of new blade survey positions
5130 DATA 0.,0625,.125,.1875,.25,.3125,.3437%,.375,.4062%,.4375,.4687%,.5,.51.7%
       ,.5625,.59375,.625,.65625,.6875,.71875,.75,.78125,.8175,.84375,.875,.90975,.9125
5131 DATA .9375,1.0,1.13125,1.2625,1.38375,1.505,1.65625
5137 DATA .9375,1.0,1.10,1.30,1.54,1.72,1.80
5134 REAU Y(*)
5140 !
5150 FOR I=1 TO Scan_max
5160     P_inf(I)=Pat2N.I)
5170     P_e(rc(I)=Pat30.I)
5180     P_ref(I)=Pat31.I)
5190     P1(I)=Pat32.I)
5200         !
5410     0(1)=P_ref(I)-P_inf(I)
```

Figure D1.   (cont)   Program   "NEW_READ_ZOC1"

50

```
5410
5420      [I DI PH[1],PL[1],Fmn2[1]
5480 NEXT I
5490 !
5500 FOR I = 1 TO Sean nns
5510 [1 DI I  rel[I],PC[I,Fm[I]
5520 NEXT I
5530 !
5540 FOR I = 1 TO Sean nns
5550 [1 DI  rel[I],PL[I],Fm[I]
5560 NEXT I
5570 !************************
5580 !!begin calibration routine to determine x_vel and gamma from data
5590 !!Interpo  ate X_vel to determine X_calib probe phi_read
5600 !!Fitgamma to Phi = Bata*beta_probe X coefficient
5610 FOR I=1 TO Sean nns
5620 !!Value needed for two probes
5630 P0[I]=Fm[32,1]
5640 P2[I]=[I]=P0[24,1]
5650 P3=[I]=Fm[25,1]
5660 !!calculate coefficients
5670 P2*[I]=[I][I]  P3[I]*P?  2
5680 P0*  p[I]=P0[I]+P2[I]+P3[I]*[I]
5690 Gamma p[I]=P[I]  ?  +[I]*P0[I]+P?3[I]
5700 !
5710 !!calculate  x_vel from beta*fit calibration routine
5720 X_vel[I]= 1735315.?8*(beta_p[I]-6428716.03*beta_ p[I]+10040.  0*beta___
     [1.4](15.4B0*beta_p[I]  ?  ?4.712*beta_p[I]-2130.12*beta  p[I]+?0?
5730 !!(bcta.x-c[I]=SQR(x(?(Gamma  1)**X_vel[I])**?/(?...
5740 !
5750 P_vel[I]=P[I]3+(1-X_vel[I]*?2)*(Gamma+1(Gamma-1))
5760 !
5770 !!calculate angle from calculated gamma values
5780 Phi_1[I]=-.015*Gamma_p[I]-2*3.984*Gamma_p[I]*2*13.751*_gma  p[I]  I]
5790 Phi_2[I]=-.155*Gamma_p[I]+34.427*Gamma_p[I]+412.145*Gamma_p[I]  6?I
5800 Phi_3[I]=+9.807*Gamma_p[I]+3-5.526*Gamma_p[I]+9.908*Gamma_p[I]  9[I]
5810 Phi_4[I]=+15.149*Gamma_p[I]+3-3.289*Gamma_p[I]+2+1.014*Gamma_p[I]  ?[I]
5820 Phi_5[I]=+15.897*Gamma_p[I]+3-5.546*Gamma_p[I]+155*Gamma_p[I]  2 ?I
5830 Phi_6[I]=+3.240*Gamma_p[I]+3.520*Gamma_p[I]+5.238*Gamma_p[I]  2 ??
5840 Phi_7[I]=+1.242*Gamma_p[I]+3-2.607*Gamma_p[I]+2+13.734*Gamma_p[I]  ??9
5850 Phi_8[I]=+1.988*Gamma_p[I]+3-3.611*Gamma_p[I]+2+14.567*Gamma_p[I]  ??7
5860 !
5870 !!x_vel average values to be used to interpolate between phi data
5880 X_avg_1=.18498269
5890 X_avg_2=.13974500
5900 X_avg_3=.10120503
5910 X_avg_4=.21922597
5920 X_avg_5=.20502024
5930 X_avg_6=.30070142
5940 X_avg_7=.27779766
5950 X_avg_8=.36982608
5960 !
5970 !!determine upper and lower bounds of X_vel and Phi for interpolation
5980 !
5990 If  X_vel[I]<=X_avg_1 AND x_vel[I]<X_avg_1 THEN
6000 X_upper=x_avg_2
6010 X_lower=X_avg_1
6020 Phi_upper=Phi_2[I]
6030 Phi_lower=Phi_1[I]
6040 END If
6050 If  X_vel[I]>X_avg_2 AND x_vel[I]<X_avg_3 THEN
6060 X_upper=X_avg_3
6070 X_lower=X_avg_2
6080 Phi_upper=Phi_3[I]
6090 Phi_lower=Phi_2[I]
6100 END If
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

51

```
5661 IF   ...  A_avg 3 (AND ... vel[I]>=X_avg 4 THEN
5670 X_upper=X_avg_4
5671 X_lower=X_avg_3
5672 Phi_upper=Phi_4[I]
5673 Phi_lower=Phi_3[I]
5674 END IF
5675 IF X_vel[I]<=X_avg_4 AND X_vel[I]>=X_avg_5 THEN
5676 X_upper=X_avg_5
5677 X_lower=X_avg_4
5678 Phi_upper=Phi_5[I]
5679 Phi_lower=Phi_4[I]
5680 END IF
5681 IF X_vel[I]<=X_avg_5 AND X_vel[I]>=X_avg_6 THEN
5682 X_upper=X_avg_6
5683 X_lower=X_avg_5
5684 Phi_upper=Phi_6[I]
5685 Phi_lower=Phi_5[I]
5686 END IF
5687 IF X_vel[I]<=X_avg_6 AND X_vel[I]>=X_avg_7 THEN
5688 X_upper=X_avg_7
5689 X_lower=X_avg_6
5690 Phi_upper=Phi_7[I]
5691 Phi_lower=Phi_6[I]
5692 END IF
5693 IF X_vel[I]<=X_avg_7 AND X_vel[I]>=X_avg_8 THEN
5694 X_upper=X_avg_8
5695 X_lower=X_avg_7
5696 Phi_upper=Phi_8[I]
5697 Phi_lower=Phi_7[I]
5698 END IF
5649 !
5650 ! Lagrange interpolation to find the deviation angle
5651 Xm=X_vel[I]
5652 Yans=0
5653 X_interp[1]=X_lower
5654 X_interp[2]=X_upper
5655 F_interp[1]=Phi_lower
5656 F_interp[2]=Phi_upper
5657 FOR J=1 TO N_pts
5658 Z=1
5659 FOR K=1 TO N_pts
5660 IF J=K THEN
5661 GOTO 5661
5662 END IF
5663 Z=Z*(Xm-X_interp[K])/(X_interp[J]-X_interp[K])
5664 NEXT K
5665 Yans=Yans+(Z*F_interp[J])
5666 NEXT J
5667 Phi_dev[I]=0.4-Yans
5668 NEXT I
5669 !************************************************
5670 !Not Loss coefficient calculation in this position
5671 !************************************************
5672 ! Plot Pstatic calculated above.
5673 FOR I=1 TO Scan_max
5674 PLOT P_st[I],Y[I],Pen2[I]
5675 NEXT I
5676 PAUSE
5677 CLEAR SCREEN
5678 !Print results to Think-Jet
5679 PRINTER IS CRT
5680 INPUT "Deviation angle and X_vel data to CRT or Printer (0=CRT,1=Print)",Ip
5681
5682 IF Ip=1 THEN PRINTER IS 702
5683 CLEAR SCREEN
5684 !
```

Figure D1   (cont)   Program   "NEW_READ_ZOC1"

52

```
5686 PRINT USING "18,"------------------------------------------------";Rev_Angle "deg."
     vel";F";"     "Rev Angle (deg)"
5698 PRINT "-----------------------------------------------------------"
5697 FOR I=1 TO Scan_max
5698 PRINT USING "3X,SZD,4D,5X,2D,6D,3X,6D,6D,6X,4D,6D,5X ...";Rev_Gr,ts ...
     Beta_p(I),X_vel(I),ref(I),ref(I),Pitch(I)
5699 NEXT I
5699 ...........................................................
5691 !.....       output section
5697 !...............................................................
5699 !
5695 ! Use subroutine to calculate the vvel and plot to landscape ...
5698 FOR I=1 TO Scan_max
5697 !     s=Gamma_p(I)
5699 !     H_np=beta_p(I)
5700 CALL vvel_poly(6,np,P_np,s,np,P_sp)
5701 !     s_vel_r(I)=X_cp
5702 !     Pitch_p(I)=8.4 ! sp
5703 !     st_pr(I)=P(1)+(1) X_vel_p(I)*(2)*(Gamma/Gamma...
5704 NEXT I
5705 PRINT
5706 PRINT
5707 PRINT
5709 PRINT "Calculated Values using Newtonian Iteration."
5710 PRINT USING "7,3X,F,,r,F,P,3,7X,F,7X,P,DY,F";"Rev(I)ee","Pctv","...
     vel","F","st","Rev Angle (deg)"
5711 FOR I=1 TO Scan_max
5713 PRINT USING "1X,SZD,4D,5X,SD,6D,3X,SD,6D,6X,4D,6D,5X ...";Rev_Gr,ts ...
     Beta_p(I),Gamma_p(I),X_vel_pr(I),P_st_pr(I),Pitch_pr(I)
5714 NEXT I
5714 !
5715 PRINTER IS CRT
5716 PAUSE
5717 !
5718 INPUT "Would you like to make another plot (Y=yes,N=no)?",Ga$
5719 IF Ga$="Y" THEN Plot_pt
5720 !
5721 CLEAR SCREEN
5722 !
5723 PRINT
5724 PRINT
5725 DISP "Now calculating cascade loss coefficient"
5726 ! Loss calculation begins here.
5727 !ncb
5728 !
5729 ALLOCATE REAL BZ(1:Scan_max)
5731 ALLOCATE REAL X1_ref(1:Scan_max)
5732 ALLOCATE REAL I4_array(1:Scan_max)
5733 ALLOCATE REAL I1_array(1:Scan_max)
5734 ALLOCATE REAL I3_num(1:Scan_max)
5735 ALLOCATE REAL I3_den(1:Scan_max)
5736 ALLOCATE REAL I2_array(1:Scan_max)
5737 ALLOCATE REAL I1_array(1:Scan_max)
5738 INTEGER Hipoint,Lowpoint,High_i,Low_i
5739 REAL Xa_i
5741 B1=56.19        ! Betal in degrees
5742 FOR I=1 TO Scan_max
5742    BZ(I)=B1-(G_4-P(1)+B(I))
5744    X1_ref(I)=SQR(1+E*P(I)/Gamma-1)/Gamma)*(1.0(6P_in(I)*_+_ref(I))+...
5745    I4_array(I)=COS(BZ(I))*(SIN(BZ(I))/P_ref(I))*(X_vel(I)*ref(I)+... ref(I) *
        na +(I)*st_ref(I)+1.0(X_l_ref(I)*2)*((Gamma/Gamma-1)+...
5745    I1_array(I) = X1_array(I)
5747    I2_array(I)=COS(BZ(I))*(SIN(BZ(I))*P_ref(I)+_+ref(I)+_st_ref(I)+ne+...
        (I) *2)((Gamma-1)/(X1_ref(I))*2(1+X_l_ref(I)*2)*(Gamma...
5747    I3_num(I)=P(I)/(1+ref(I))*(COS(BZ(I))*2)*2*(Gamma/(Gamma-1))+...
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

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```
7/2*(1_x_velt[i]*2)*(1/(Gamma-1)))*(1-x_velt[2/2/(Gamma-Gamma-1)))
5749    I3_new[]=X1_ref[1]*2*(1-X1_ref[]*2)^(1/(Gamma-1))
5750    I3_array[]=I3_num[]/I3_den[]
5751    !
5752 NEXT I
5753 ! Begin calling subroutines to determine u pper interval of integration
5754 Lowpoint=1
5755 Hipoint=33
5756 CALL Dat_int(Lowpoint,Hipoint,I4_array(*),Y(*),I4_int_lo,I4_int_hi,Xe_I)
5757    Value2_High_i_Low_i
5757 PRINT "VALUE1="iValue1
5758 PRINT "VALUE2="iValue2
5759 PRINT "I    ="iHigh_i
5760 PRINT "I-I   ="iLow_i
5762 !Return the index values to interpolate between when calculating I1,I2,I3
5763 !interpolate to find proper inverse position for one blade space
5764 Xs_i=1.0
5765 Xxs_i
5767 CALL Interpolate(Value1,Value2,Posit1,Posit2,Probs,posit,Xe_I)
5768 PRINT "Probe position for one blade space ="iProbe_posit
5770 PAUSE
5165 ! BEGIN VALUES TO CHECK SUBPROGRAMS
5166 ! Probe posit=1.6345
5167 !*****************************************************
5168 ! Begin calculations of I1,I2,I3 by calling Dat_int subprogram
5169 ! Define the upper and lower points of the integrals
5170 Lowpoint=1
5171 CALL Dat_int(Lowpoint,High_i,I1_array(*),Y(*),I1_int_hi)
5172 CALL Dat_int(Lowpoint,Low_i,I1_array(*),Y(*),I1_int_lo)
5173 CALL Interpolate(Value1,Value2,I1_int_lo,I1_int_hi,I1_int,Xe_I)
5174 PRINT "I1_INT ="iI1_int
5175 PAUSE
5176 !
5177 CALL Dat_int(Lowpoint,High_i,I2_array(*),Y(*),I2_int_hi)
5178 CALL Dat_int(Lowpoint,Low_i,I2_array(*),Y(*),I2_int_lo)
5179 CALL Interpolate(Value1,Value2,I2_int_lo,I2_int_hi,I2_int,Xe_I)
5180 PRINT "I2_INT="iI2_int
5181 PAUSE
5182 !
5183 CALL Dat_int(Lowpoint,High_i,I3_array(*),Y(*),I3_int_hi)
5184 CALL Dat_int(Lowpoint,Low_i,I3_array(*),Y(*),I3_int_lo)
5185 CALL Interpolate(Value1,Value2,I3_int_lo,I3_int_hi,I3_int,Xe_I)
5186 PRINT "I3_INT ="iI3_int
5187 PAUSE
5188 REAL Pt_ref_avg
5189 REAL x_ref_avg
5190 REAL Q_ref_avg
5191 REAL y_ref_avg
5192 REAL P_ref_avg
5194 x_ref_avg=0
5195 Pt_ref_avg=0
5196 Q_ref_avg=0
5197 P_ref_avg=0
5199 FOR I=1 TO High_i
5200    x_ref_avg=X1_ref[I]*X_ref_avg
5201    Pt_ref_avg=Pt[I]*Pt_ref_avg
5202    Q_ref_avg=P_ref[I]*Q_ref_avg
5203    P_ref_avg=P_ref[I]*P_ref_avg
5205 NEXT I
5206 x_ref_avg=x_ref_avg/High_i
5207 Pt_ref_avg=Pt_ref_avg/High_i
5208 Q_ref_avg=Q_ref_avg/High_i
5209 P_ref_avg=P_ref_avg/High_i
5211 !
5212 !*****using I1,I2,I3 calculate A,B,C,D,E
5213 A=x*(I2_int/I1_int)*XX_ref_avg
5214 B1=(I1_int/I1_int)*XX_ref_avg
5215 C1=(1/Gamma-1)X(Gamma-1))*2
```

Figure D1. (cont)   Program   "NEW_READ_ZOC1"

54

```
6216 Di=2*SQRT((C1)*(1-((2*Gamma)/(Gamma-1))*Ai^2) Bi^2
6217 Ei=Bi^^Ai^^2*(1-((2*Gamma)/(Gamma-1))*Ai^^2)^2
6218 X3_num=SQRT((-Di+SQRT(Di^^2-4*Ci*Ei))/(2*Ci))
6220 X3_sub=SQRT((-Di-SQRT(Di^^2-4*Ci*Ei))/(2*Ci))
6221 PRINT "X3_SUB =";X3_sub
6222 X3_mixed=X3_sub
6223 UEG
6224 Beta3_mixed=ASN(Ai/(1_mixed)
6225 PT43=(P1_ref_avg*X_ref_avg/(1+X_ref_avg^2))((1//(Gamma-1)))+ +[c! +[c! +[cf +[cf]
1+X3_mi+ed*3^3(1//(Gamma-1))/(COS(BetaS_mixed))
6226 P43=(1_intef3_ref_avg*X_ref_avg/(1+X_ref_avg^2))((1//(Gamma-1))+[+[Pcbxl3
+X3_mixed(*3_mixed(*3_mixed 3^)^(1/(Gamma-1))
6229 X_mixed=P_ref_avg/(13)/3_ref_avg)
6274 PRINT "Device to print results (@=CRT 1=PRINTER)";Dev
6235 IF de==1 THEN PRINTER IS 707
6231 CLEAR SCREEN
6232 PRINT "14 UPPER = ";Value2
6233 PRINT "14 LOWER = ";Value1
6234 PRINT "X3_mixed = ";X3_mixed
6235 PRINT "P_ref_avg ";P_ref_avg
6236 PRINT "P13_mixed ";P13
6237 PRINT "Beta3_mixed=";(BetaS_mixed)
6238 PRINT "M_mixed  =";M_mixed
6239 PAUSE
6240 !
6241 ! Plot ostatic that was calculated by Newtonian iteration
6242 !
6243 CLEAR SCREEN
6244 PRINTER IS CRT
6245 CALL Plot
6246 FOR I=1 TO Scan_max
6247    PLOT P_exit(I),Y(I),Pen2(I)
6248 NEXT I
6249 FOR I=1 TO Scan_max
6250    PLOT P_st_p(I),Y(I),Pen2(I)
6251 NEXT I
6252 PAUSE
6253 !Deallocate all real variables
6254 !
6255 DEALLOCATE Pen2(*)
6260 DEALLOCATE P_inf(*)
6257 DEALLOCATE P_exit(*)
6258 DEALLOCATE P_ref(*)
6259 DEALLOCATE M_inf(*)
6260 DEALLOCATE M_exit(*)
6261 DEALLOCATE Ma1(*)
6262 DEALLOCATE Ma2(*)
6270 DEALLOCATE Ma3(*)
6280 DEALLOCATE Ma4(*)
6290 DEALLOCATE Q(*)
6300 DEALLOCATE Pt(*)
6310 DEALLOCATE Y(*)
6311 !*******************************
6312 !Deallocate added variables
6313 DEALLOCATE FZ_1(*)
6314 DEALLOCATE P_pt(*)
6315 DEALLOCATE P_st_pi(*)
6317 DEALLOCATE P3_r(*)
6318 DEALLOCATE Pitch(*)
6319 DEALLOCATE Pitch_p(*)
6320 DEALLOCATE X_val_p(*)
6321 DEALLOCATE Beta_p(*)
6322 DEALLOCATE Gamma_p(*)
6324 DEALLOCATE X_interp(*)
```

Figure D1. (cont)   Program   "NEW_READ_ZOC1"

```
6355 Deallocate F_interp(*)
6320 DEALLOCATE F2i(*)
6321 DEALLOCATE Mech_swel(*)
6325 DEALLOCATE Phi_1(*)
6327 DEALLOCATE Phi_2(*)
6330 DEALLOCATE Phi_3(*)
6331 DEALLOCATE Phi_4(*)
6332 DEALLOCATE Phi_5(*)
6333 DEALLOCATE Phi_6(*)
6334 DEALLOCATE Phi_7(*)
6335 DEALLOCATE Phi_8(*)
6336 DEALLOCATE X1_refit(*)
6337 DEALLOCATE I4_arra(*)
6339 DEALLOCATE I2_arra(*)
6340 DEALLOCATE I1_arra(*)
6341 DEALLOCATE I3_num(*)
6342 DEALLOCATE I3_dem(*)
6343 DEALLOCATE D3(*)
6345 !.................................................
6346 KEY LABELS ON
6347 !PRINTER IS CRT
6348 !
6350 !GOTO First
6360 !
6370 !.................................................
6390 !EXIT PROGRAM AND DEALLOCATE ALL BUFFERS AND PATHS
6391 !.................................................
6400 !
6410 Deallocate: !
6420 ASSIGN @Data_path1 TO *
6430 ASSIGN @Data_path2 TO *
6440 DEALLOCATE Cal(*)
6450 DEALLOCATE Data(*)
6460 DEALLOCATE Pa(*)
6470 RETURN
6480 !
6490 !
6490 Finish: !
6500 IF allocated=1 THEN GOTO Deallocate
6510 PRINTER IS CRT
6520 LOAD "ZOP_MENU",10
6530 END
6540 !
6550 !.................................................
6560 !SUBROUTINE TO SET UP GRAPHICS WINDOW
6570 !.................................................
6580 !
6590 SUB Plot
6600 !
6610 !Subroutine to display plot screens, ins= the plot of any curves
6620 !for the specified variables in the COM/Plot_labels/ line.
6630 !
6640 COM /Plot_labels/ Xo,Xf,Yo,Yf,Dx,Dy,Title$,X_label$,Y_label$
6650 CLEAR SCREEN
6660 KEY LABELS OFF
6670 GINIT                        !Initialize graphic options
6690 X_range=Xf-Xo               !Length of X-axis
6690 Y_range=Yf-Yo               !Length of Y-axis
6700 LORG 6                      !Character ref plct=g center
6710 MOVE 100*RATIO/2,100        !Move cursor to screen loc for labels
6720 CSIZE 3                     !Sizes labeling
6730 LABEL Title$                !Plot title
6740 MOVE 100*RATIO/2,0         !Move cursor to action center screen
6750 LORG 4                      !Character ref at bottom center
6760 LABEL Y_label$             !X-axis label
6760 LDIR 90                     !Degrees for LDIR
6770 DEG
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

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```
6720  ! LINE=IZR                             !SPRIT ' X-AXIS LABEL AT END
6730  LORG 6
6800  MOVE 0,60
6810  LABEL Y_label$                         !Y-axis label
6820  LDIR 0
6830  LORG 1                                 !Reset label to horizontal orientation
6840  VIEWPORT IP.90+RATIO,IP.90             !Sets up new screen size
6850  FRAME                                  !Draw around viewport
6860  WINDOW Xo,Xf,Yo,Yf                     !Set axis lengths in USER units
6870  AXES x_range/Dx,y_range/Dy,Xo,Yo       !Draws axes at tick marks
6880  AXES x_range/Dx,y_range/Dy,Xf,Yf       !Draws axes at upper right
6890  GRID x_range/Dx,y_range/Dy,Yo,Yo,Dx,Dy,.001
6900  CLIP OFF                               !Sm label comes out outside VIEWPORT
6910  CSIZE 3.0,.4                           !Sets label size
6920  LORG 6                                 !Number Y-axis
6930  FOR I=Yo TO Yf STEP y_range/Dy
6940       MOVE 1,Yo,.01+Y_range
6950       LABEL USING "#,I";I
6960  NEXT I
6970  LORG 4
6980  FOR I=Xo TO Xf STEP x_range/Dx
6990       IF ABS(I)<1.0E-5 THEN I=0.
7000       MOVE Xo,.01+X_range,I
7010       LABEL USING "#,I";I
7020  NEXT I
7030  CLIP ON
7040  !
7050  SUBEND
7060  !
7070  SUB square(Xd,Yd,Kf,Ss)
7080  ! subroutine to plot squares around the local region designated
7090  !     (by the PLOT statement)
7100      Xd=Xd+Kf*Ss/1
7110      Yd=Yd+Kf*Ss/RATIO
7120      RPLOT -Xd,Yd,-2
7130      RPLOT Xd,Yd,-1
7140      RPLOT Xd,-Yd,-1
7150      RPLOT -Xd,-Yd,-1
7160      RPLOT -Xd,Yd,2
7170  SUBEND
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

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```
7760  SUB Rread_luc(INTEGER Lowpoint,H(pnint,Ph(0,0(*),Pos(*),I4_int,I4_int(*),I4_int
2_int,Value1,Value2,INTEGER High_i,Low_i)
7770  ALLOW PAGE 1
7770  DIM A(198)
7770  DIM B(198)
7740  DIM x(198)
7750  DIM Dint(100)
7760  DIM Deint(100)
7770  MAT A= (0)
7780  MAT B =(0)
7790  MAT x =(0)
7800  MAT Dint= (0)
7810  MAT Deint= (0)
7811  I4_int=0
7820  Deint=1
7830  FOR I=Lowpoint+1 TO H
7850  A(I)=-((2*Pos[I+1]-Pos[I-1]-((0[I+1]-0[I])/5/(Pos(*+1)-Pos(*-1)))/(Pos[I+1]-Pos[I-1])
3/(Pos(I)-Pos[I-1]))
7860  B(I)=(0[I]-0[I-1])/(Pos[I]-Pos[I-1])-((Pos[I]-Pos[*-1]))/(H(I)-Pos(I))
7870  X(I)=(0[I]+H[I+1]-Pos[I]*Pos^*0[H(I]*Pos(I))
7880  NEXT I
7890  Dint(I)=A(2)*(Pos[2]-3.Pos(I)*3)/3.0*B(2)*(Pos(2)^2-Pos(I)^2)/2+H(I)*(Pos
x(2)-Pos(I))
7900  Dint(I)=int(N)+(Pos[N+1]-3-Pos[H]*3)/3.0*B[H]*Pos(N+1)^2-Pos(N+1)^2-Pos(N)^2)/2+x(N)
*(Pos[H+1]-Pos[N]))
7920  FOR I=Lowpoint+1 TO H+1
7930  Dint(I)=(A[I]*(Pos[I+1]*3-Pos[I+1]^3-Pos[I]^2)/3)/6+B(I)*(Pos[I+1]^2-(Pos[I+1]^2)/2+x*Pos
x(I)*2*4+(0[I]+0[I+1])*Pos[I+1]*Pos[I])/2
7940  NEXT I
7950  FOR I=1 TO N
7960     I4_int=I4_int+Dint(I)
7970     IF I4_int>=I4_int/1.0 THEN
7980        Pos(I2)=Pos(I)
7990        Pos(I1)=Pos(I-1)
8000        Value2=I4_int
8010        Value1=I4_int-Dint(I)
8011        High_i=(I)
8012        Low_i=(I-1)
8014        GOTO 8040
8020     END IF
8030  NEXT I
8031  Pos(I2)=Pos(I)
8032  Pos(I1)=Pos(I-1)
8033  Value2=I4_int
8034  Value1=I4_int-Dint(N)
8035  High_i=I(I+1)
8036  Low_i=(I)
8040  SUBEND
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

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```
8060  SUB Interpolate(X_low,X_high,Y_lower,Y_upper,Xnew,I,Sc,I)
8065  OPTION BASE 1
8080  Ynew L=0
8085  INTEGER L,E
8092  DIM Y(15)
8095  DIM F(15)
8100  MAT Y = (B)
8105  MAT F = (B)
8110  X(1)=Y_low
8120  X(N)=Y_high
8130  F(1)=Y_lower
8140  F(2)=Y_upper
8155  N_pt=I=2
8160  FOR I=1 TO N_ptet
8180     FOR I=1 TO N_pt=1
8190        IF I <> I=1 THEN
8200           GOTO 8230
8210        END IF
8220        Zl=Zl*(Xa_1-F(1)F)/(X(I)-X(L))
8232     NEXT L
8240     Ynew_l=Ynew_l+(Z1*F(L)Y)
8250  NEXT I
8250  SUBEND
8260  SUB Int_int(INTEGER I,Npoint,Hlpoint,REPN, D(*),F(*), Int(*))
8265  ! Simpson integration program Ref. NPS-S72C20071A
8280  OPTION BASE 1
8290  DIM A(100)
8300  DIM D(100)
8310  DIM G(100)
8320  DIM Dint(100)
8330  MAT A= (B)
8340  MAT D= (B)
8350  MAT G= (B)
8360  MAT Dint= (B)
8370  N=Npoint-I
8380  Rel=N-I
8390  FOR I=I=Npoint+I TO N1
8400     A(I)=I=0/(R(I=1)-R(I=1))*(D(I=1)-D(I))/(R(I=1)-R(I))-(D(I)-D(I=1))/(R(I)-R(I=1)))
8410     D(I)=(D(I)-D(I=1))/(R(I)-R(I=1))-R(I)*R(I=1)*A(I)
8420     G(I)=D(I)-A(I)*(R(I)*2-R(I=1))
8430  NEXT I
8440  Dat_int=0
8450  FOR I=Npoint+I TO N1
8455     Dint(I)=(A(I)*(R(I)*3-R(I=1)*3)/3.0+B(I)*(R(I)*2-R(I=1)*2)/2.0+D(I)*(R(I)-R(I=1))
             +A(I)*(R(I)*3-R(I=1)*3)/3.0+B(I)*(R(I)*2-R(I=1)*2)/2.0
8470     Dat_int=Dat_int+Dint(I)
8460  NEXT T
8490     Dint(I)=A(I)*(R(I)*3-R(I=1)*3)/3.0+B(I)*2*(R(I)*2-R(I=1)*2)/2.0+D(I)*(R(I)-R(I=1))
8500     Dint(N)=A(N)*(R(N)*3-R(N=1)*3)/3.0+B(N)*(R(N)*2-R(N=1)*2)/2.0+D(N)*(R(N)-R(N=1))
             +A(N))
8510     Dat_int=Dat_int+Dint(I)+Dint(N)
8520  SUBEND
```

Figure D1. (cont) Program "NEW_READ_ZOC1"

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APPENDIX E. MIXED-OUT LOSS CALCULATION

The calculation of the total pressure loss coefficient in the fan-blade cascade model required the calculation of fully-mixed-out-flow conditions. This requirement was difficult due to the probe not traversing parallel to the trailing edge of the blades, and the use of uneven spacings. Figure E1 shows the fully-mixed-out control volume for the analysis, and the location of the traverse in the fan blade cascade model .
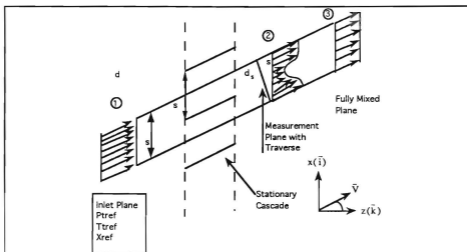

Figure E1.   Fully-Mixed-Out Control Volume

The equations for the analysis, reported by Armstrong [Ref. 12], were programmed in HP Basic and are part of the data reduction program "NEW_READ_ZOC1" listed in Appendix D. The analysis required that the probe data be taken over a single blade space. Due to the probe traverse not traversing parallel to the trailing edge, it was required that the program calculate when the

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probe had measured the same integrated mass flux at position 2 as had entered at position 1(where nozzle free-stream conditions were known). The integral in equation 1 was programmed as a subprogram labeled "Mass_flux".

$$1 = \int_{0}^{\frac{d_s}{d_1}} \frac{X_2(1-X_2)^{\frac{1}{\gamma-1}}}{Xref(1-Xref)^{\frac{1}{\gamma-1}}} \cdot \frac{P_{T2}}{P_{T1}} \cdot \cos\beta_2 d(\frac{x}{d_1}) \qquad (1)$$

where d_1 is the staggered passage width of 1.656 inches and d_s is the blade traverse distance required for the analysis. By computing the integral at every point in the traverse, the distance d_s was determined where the integral became unity. Once the proper blade space distance was known the following equations could be calculated using the subprogram "Dat_int" which was an integration scheme designed to integrate a function over non-equispaced points.

$$\hat{I}_1 = \int_{0}^{1} \frac{X_2(1-X_2)^{\frac{1}{\gamma-1}}}{Xref(1-Xref)^{\frac{1}{\gamma-1}}} \cdot \frac{P_{T2}}{P_{Tref}} \cdot \cos\beta_2 d(\frac{x}{s}) \qquad (2)$$

$$\hat{I}_2 = \int_{0}^{1} \frac{X_2^2(1-X_2)^{\frac{1}{\gamma-1}}}{Xref^2(1-Xref^2)^{\frac{1}{\gamma-1}}} \cdot \frac{P_{T2}}{P_{Tref}} \cdot \cos\beta_2 \sin\beta_2 d(\frac{x}{s}) \qquad (3)$$

$$\hat{I}_3 = \int_0^1 \frac{\left[(1-X_2{}^2)^{\frac{\gamma}{\gamma-1}} + (\frac{2\gamma}{\gamma-1}) \cdot X_2{}^2 (1-X_2{}^2)^{\frac{1}{\gamma-1}} \cdot \cos^2 \beta_2 \right]}{Xref^2 (1-Xref^2)^{\frac{1}{\gamma-1}}} \cdot \frac{P_{T2}}{P_{Tref}} \cdot d(\frac{x}{s}) \quad (4)$$

$$\hat{A} = Xref \cdot \frac{\hat{I}_2}{\hat{I}_1} = X_3 \sin \beta_3 \quad (5)$$

$$\hat{B} = Xref \cdot \frac{\hat{I}_3}{\hat{I}_1} = \frac{\left[(1-X_3{}^2) + (\frac{2\gamma}{\gamma-1})X_3{}^2 \cos^2 \beta_3 \right]}{X_3 \cos \beta_3} \quad (6)$$

$$C = \left(\frac{\gamma+1}{\gamma-1}\right)^2 \quad (7)$$

$$D = 2\left(\frac{\gamma+1}{\gamma-1}\right)\left[1-\left(\frac{2\gamma}{\gamma-1}\right)\hat{A}^2\right] - \hat{B}^2 \quad (8)$$

$$E = \left[1-\left(\frac{2\gamma}{\gamma-1}\right)\hat{A}^2\right]^2 + \hat{A}^2 \hat{B}^2 \quad (9)$$

$$X_3{}^2 = \frac{-D \pm \sqrt{D^2 - 4CE}}{2C} \quad (10)$$

where the subsonic root of X_3 is chosen

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$$\beta_3 = \sin^{-1}\left(\frac{\hat{A}}{X_3}\right) \tag{11}$$

$$P_{T3} = \frac{Xref\left(1 - Xref^2\right)^{\frac{1}{\gamma-1}} P_{Tref}\,\hat{I_1}}{X_3\left(1 - X_3\right)^{\frac{1}{\gamma-1}}\cos\beta_3} \tag{12}$$

The fully-mixed-out loss coefficient could be then be calculated using the inlet total pressure, the fully-mixed-out total pressure, and inlet static pressure in Equation 13.

$$\varpi = \frac{Ptref - Pt_3}{Ptref - Pstaticref} \tag{13}$$

When the above procedure was followed using the baseline test data, the values obtained for d_s were significantly greater than 1.656 inches. In reducing the baseline data, the fully-mixed-out condition was calculated using Eq. (2) - Eq.(12), with the full survey distance (s), which was 1.656 inches.

APPENDIX F. SELECTED RAW DATA

```
Data Print Out for Run # 1 , Run # 2 , File7B141424;
     Period between samples (sec): .0030303030303
     Sample collection rate (Hz): 330
     Number of samples per port: 10
     Length of data run (sec): 11
     the scan type is: 3
     Number of scans/traverses: 33
     Increment of traverse: .0625  inches
     Atmospheric pressure is: 14.72  psia
     Tunnel Pressure Ratio is: 2.11030215729
```

Scan	Port Number						
	1	24	25	29	30	31	32
1	15.410	47.191	45.052	15.463	32.632	53.769	51.636
2	15.410	47.276	45.023	15.483	32.642	53.714	51.507
3	15.388	47.257	44.976	15.473	32.662	53.762	51.550
4	15.443	46.982	44.769	15.483	32.622	53.741	51.204
5	15.399	46.982	44.712	15.533	32.582	53.650	51.170
6	15.399	46.906	44.562	15.543	32.562	53.849	51.112
7	15.377	47.001	44.610	15.483	32.562	53.750	51.100
8	15.356	47.097	44.741	15.503	32.602	53.804	51.200
9	15.421	47.096	44.694	15.513	32.542	53.805	51.312
10	15.291	46.782	44.429	15.513	32.462	53.608	50.921
11	15.356	46.915	44.543	15.513	32.552	53.750	51.095
12	15.388	47.343	44.801	15.473	32.442	53.714	51.493
13	15.387	47.428	44.910	15.483	32.590	53.627	51.607
14	15.453	46.372	43.844	15.533	32.552	53.660	50.433
15	15.399	42.269	40.175	15.503	32.552	53.641	45.398
16	15.410	41.344	39.461	15.483	32.542	53.657	43.554
17	15.432	39.783	38.008	15.463	32.502	53.741	40.895
18	15.346	41.919	41.025	15.483	32.532	53.569	44.408
19	15.399	46.239	45.230	15.523	32.502	53.772	50.625
20	15.421	46.801	45.508	15.523	32.502	53.723	51.303
21	15.367	46.744	45.522	15.523	32.532	53.623	51.246
22	15.432	46.649	45.456'	15.463	32.502	53.641	51.265
23	15.464	46.502	45.512	15.533	32.472	53.723	51.227
24	15.356	46.497	45.597	15.543	32.512	53.762	51.109
25	15.410	46.431	45.456	15.543	32.442	53.632	50.980
26	15.464	46.420	45.569	15.513	32.522	53.760	51.004
27	15.377	46.296	45.560	15.543	32.552	53.695	51.007
28	15.443	46.382	45.662	15.533	32.442	53.632	51.036
29	15.399	46.229	45.860	15.483	32.502	53.632	51.046
30	15.399	46.372	45.906	15.503	32.512	53.660	51.191
31	15.432	46.277	46.093	15.543	32.462	53.705	51.170
32	15.399	46.105	46.206	15.543	32.522	53.675	51.131
33	15.421	46.210	46.196	15.513	32.442	53.680	51.360

Figure F1.   Run 2   2/24/94   Raw Data

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Position	Rmin	Gamma	X_vel	P_at	θ
+0.00000	+.105080	+.387042	+.336411	+/4.004164	+7.290
+.06250	+.105251	+.417036	+.337512	+33.046272	.696
+.12500	+.105312	+.421933	+.334703	+41.31394	7.239
+.18750	+.106162	+.409132	+.331715	+41.36502	+7.500
+.25000	+.104412	+.4?603	+.334613	+41.32903	+7.510
+.31250	+.105232	+.329261	+.331375	+41.049920	7.076
+.37500	+.105249	+.34?205	+.331157	+43.72030	+7.640
+.43750	+.103303	+.443033	+.330003	+43.42502	+7.041
+.50000	+.106524	+.444200	+.332702	+43.06046	7.101
+.56250	+.104789	+.417623	+.328762	+43.421739	+1.075
+.62500	+.104318	+.449900	+.328561	+41.717005	+7.075
+.68750	+.104315	+.464603	+.328651	+42.579751	+7.505
+.75000	+.105176	+.463002	+.331474	+41.129000	+7.130
+.81250	+.102965	+.502041	+.332532	+32.925000	+7.578
+.87500	+.091092	+.501652	+.292027	+37.797000	+1.077
+.93750	+.072363	+.502544	+.256404	+44.322172	+8.556
+1.00000	+.012376	+.456134	+.191402	+48.194093	+.938
+1.06250	+.061044	+.108396	+.235659	+48.052720	.909
+1.12500	+.096589	+.205269	+.309209	+35.900539	+.428
+1.18750	+.099762	+.240064	+.316309	+35.473521	.001
+1.25000	+.099773	+.239109	+.316327	+35.451603	+.022
+1.31250	+.101877	+.228094	+.321304	+35.062719	+.578
+1.37500	+.101110	+.206600	+.319072	+35.109505	+.150
+1.43750	+.100453	+.174906	+.310125	+35.030047	.033
+1.50000	+.098059	+.195100	+.319959	+35.559560	+.007
+1.56250	+.099627	+.167338	+.315960	+35.352626	.009
+1.62500	+.098679	+.146823	+.318090	+35.208159	.321
+1.68750	+.099239	+.143553	+.312269	+35.629702	.006
+1.75000	+.098060	+.075841	+.311923	+35.675269	1.111
+1.81250	+.097236	+.070715	+.309000	+35.931200	+.910
+1.87500	+.097407	+.038071	+.310211	+35.987320	1.602
+1.93750	+.097314	+.020165	+.310005	+35.809202	.009
+2.00000	+.100406	+.002721	+.317999	+35.395027	.160

The cascade loss coefficient based on inlet
dynamic pressure as calculated using
mass averaged quantities as shown below.

Ptmol = 51.7056520152 PSIA

Pima2 = 50.4993345376 PSIA

Ptt-Pt = 30.1956451808 PSIA

Tlavg = 514.5 deg R

W_bar = .084206392192

Figure F1. (cont) Run 2 2/24/94 Raw Data

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```
Data Print Out for Run # 1 , Run # 4 , File 701414244
     Period between samples (sec): .0030303030303
     Sample collection rate (Hz): 330
     Number of samples per run: 10
     Length of data run (sec): 31
     The scan type is: 3
     Number of scans/traverse: 33
     Increment of traverse: .0625 inches
     Atmospheric pressure (in): 14.715 psia
     Tunnel Pressure Ratio is: 2.09427217205...
```

Scan	1	24	25	29	30	31	32
1	15.097	46.494	44.282	15.312	32.069	52.911	50.021
2	15.140	46.542	44.301	15.222	32.159	52.939	50.001
3	15.053	46.428	44.253	15.277	32.129	52.857	50.202
4	15.042	46.248	43.984	15.207	32.010	52.994	50.457
5	15.195	46.227	43.941	15.199	32.199	52.920	50.008
6	15.086	46.112	43.798	15.272	32.029	53.039	50.129
7	15.075	46.190	43.836	15.282	32.109	52.925	50.207
8	15.107	46.246	43.855	15.312	32.099	52.838	50.291
9	15.107	46.168	43.760	15.282	32.009	52.984	50.208
10	15.075	46.045	43.666	15.242	32.070	52.966	50.003
11	15.031	45.921	43.580	15.292	32.049	52.298	49.977
12	15.107	46.017	43.694	15.292	32.048	52.966	50.064
13	15.031	46.190	43.779	15.282	32.038	52.893	50.290
14	15.086	46.179	43.466	15.262	32.010	52.747	50.075
15	15.075	44.345	41.586	15.252	31.970	52.075	47.564
16	15.031	40.285	38.470	15.282	31.978	52.875	42.771
17	15.064	37.858	37.166	15.302	31.998	52.038	39.193
18	15.140	41.285	39.400	15.292	32.048	52.940	44.226
19	15.129	45.442	44.694	15.282	31.988	52.020	49.735
20	15.107	45.892	44.745	15.282	31.950	52.002	50.472
21	15.107	45.922	44.783	15.292	31.998	52.020	50.514
22	15.129	45.929	44.773	15.292	32.048	52.204	50.429
23	15.053	45.691	44.792	15.292	31.960	52.944	50.343
24	15.140	45.853	44.839	15.302	31.999	52.920	50.367
25	15.107	45.586	44.707	15.292	31.909	52.030	50.272
26	15.107	45.490	44.868	15.323	31.888	52.930	50.208
27	15.053	45.403	45.000	15.292	31.910	52.930	50.312
28	15.064	45.375	44.971	15.312	31.860	53.011	50.210
29	15.009	45.379	45.075	15.312	31.320	52.902	50.417
30	15.097	45.385	45.141	15.292	31.888	52.076	50.340
31	15.107	45.346	45.302	15.302	31.088	52.893	50.342
32	15.184	45.375	45.508	15.302	31.088	52.911	50.450
33	15.086	45.231	45.548	15.302	31.050	52.293	50.410

Figure F2. Run 4   2/24/94   Raw Data

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Position	Beta	Gamma		Pt	θ
+0.00000	+.106918	+.407205	+.335743	+33.439232	+3.548
+.06250	+.107439	+.409984	+.337107	+33.358166	+3.612
+.12500	+.106677	+.401569	+.335075	+33.454211	+3.445
+.18750	+.104073	+.437265	+.336100	+33.174569	+3.077
+.25000	+.102011	+.423172	+.336001	+33.195039	+3.072
+.31250	+.104200	+.444342	+.326237	+33.070165	+4.100
+.37500	+.103800	+.452525	+.327415	+33.290172	+4.283
+.43750	+.103921	+.457597	+.327471	+33.001075	+4.324
+.50000	+.104520	+.457256	+.329117	+33.013029	+4.341
+.56250	+.104380	+.455215	+.328733	+33.562294	+4.299
+.62500	+.104488	+.446434	+.329039	+33.466191	+4.147
+.68750	+.104273	+.445915	+.327794	+33.631023	+4.122
+.75000	+.103950	+.463457	+.327553	+33.740793	+4.450
+.81250	+.104172	+.520485	+.328161	+33.579769	+5.524
+.87500	+.086601	+.599904	+.309411	+33.523959	+6.795
+.93750	+.079337	+.534907	+.270226	+34.001343	+5.317
+1.00000	+.042896	+.411459	+.192636	+34.331937	+3.003
+1.06250	+.069499	+.086222	+.250035	+35.228939	-1.055
+1.12500	+.094875	+.179722	+.303954	+35.436323	1.090
+1.18750	+.102192	+.222420	+.322773	+34.344059	1.669
+1.25000	+.102727	+.219231	+.324218	+34.269020	1.629
+1.31250	+.101532	+.209210	+.320999	+34.465523	1.487
+1.37500	+.101325	+.176241	+.320444	+34.454295	1.050
+1.43750	+.101580	+.159021	+.321127	+34.400981	.170
+1.50000	+.101350	+.168022	+.320512	+34.369566	.949
+1.56250	+.100172	+.123711	+.317386	+34.664414	-.626
+1.62500	+.100061	+.008332	+.317094	+34.652676	-1.175
+1.68750	+.100457	+.079940	+.318137	+34.560756	-1.185
+1.75000	+.099596	+.059978	+.315694	+34.766803	-1.429
+1.81250	+.100239	+.044425	+.317563	+34.686893	-1.633
+1.87500	+.099511	+.005189	+.315662	+34.665673	-2.121
+1.93750	+.099865	-.036082	+.313950	+35.091164	-2.663
+2.00000	+.099613	-.062773	+.315918	+34.089373	3.004

The cascade loss coefficient based on inlet
dynamic pressure as calculated using
mass averaged quantities as shown below.

Ptma1 = 52.8913362148 PSIA
Ptma2 = 49.7055979741 PSIA

P1-P1 = 37.6061947212 PSIA
Ttavg = 513 deg R

W_bar = .0847131241109

Figure F2. (cont)   Run 4   2/24/94   Raw Data

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```
Data Print Out for Zoc # 1 , Run # 5 , FileZR1414245
    Period between samples (sec): .0303030303030303
    Sample collection rate (Hz):  330
    Number of samples per port:   10
    Length of data run (sec):     31
    The scan type is:             4
    Number of scans/traverses:    33
    Increment of traverse:        .0625  Inches
    Atmospheric pressure is:      14.71  psia
    Tunnel Pressure Ratio is:     2.1263124713
```

Scan		Port Number					
	01	24	25	29	30	31	
1	14.950	46.017	43.937	14.931	31.742	52.242	50.367
2	14.901	45.873	43.537	14.991	31.762	52.221	50.101
3	14.880	45.576	43.185	14.961	31.677	52.242	49.784
4	14.880	45.643	43.299	15.001	31.717	52.319	49.548
5	14.850	45.510	43.109	14.961	31.667	52.210	49.559
6	14.880	45.601	43.223	14.891	31.727	52.319	49.617
7	14.814	45.614	43.214	15.001	31.677	52.301	49.681
8	14.880	45.769	43.280	14.971	31.636	52.252	49.802
9	14.803	45.662	43.214	14.931	31.596	52.191	49.607
10	14.782	45.624	42.937	14.991	31.646	52.209	49.395
11	14.880	45.182	42.364	15.041	31.667	52.273	49.054
12	14.047	43.819	41.009	15.011	31.636	52.264	47.054
13	14.880	41.040	39.204	14.981	31.646	52.264	44.700
14	14.869	39.703	37.904	14.981	31.677	52.300	43.412
15	14.814	37.954	36.831	14.961	31.506	52.283	39.695
16	14.869	37.259	36.537	14.921	31.607	52.292	39.568
17	14.782	38.152	37.826	15.011	31.586	52.292	39.998
18	14.825	40.715	40.501	14.951	31.536	52.118	43.491
19	14.835	43.348	42.718	14.431	31.576	52.246	47.426
20	14.880	44.826	44.069	14.971	31.667	52.356	49.396
21	14.858	45.326	44.211	14.971	31.626	52.255	49.887
22	14.890	45.326	44.316	14.961	31.616	52.191	49.964
23	14.912	45.280	44.211	15.071	31.566	52.219	49.954
24	14.880	45.345	44.240	14.571	31.616	52.319	50.040
25	14.869	45.269	44.202	15.001	31.596	52.293	49.987
26	14.901	45.269	44.259	14.991	31.636	52.264	49.848
27	14.912	45.269	44.234	14.981	31.556	52.283	49.916
28	14.869	45.230	44.240	14.991	31.596	52.264	49.910
29	14.836	44.999	44.192	14.981	31.586	52.246	49.627
30	14.901	44.961	44.325	15.001	31.546	52.210	49.694
31	14.956	44.990	44.675	15.051	31.607	52.191	49.958
32	14.901	44.913	44.897	15.061	31.536	52.200	49.973
33	14.912	44.711	45.053	15.011	31.566	52.209	49.983

Figure F3. Run 5   2/24/94   Raw Data

Position	Beta	Gamma	X vel	D. el	6.4° − θ
+0.00000	+.108061	+.404499	+.339800		
+.12500	+.107021	+.432315	+.330244		
+.25000	+.107102	+.443102	+.335254		
+.37500	+.104235	+.457425	+.370253		
+.50000	+.105448	+.465506	+.337769		
+.62500	+.104099	+.125058	+.327847		
+.65625	+.106091	+.465464	+.353421		
+.68750	+.107498	+.467900	+.372281		
+.71875	+.104299	+.473635	+.328263		
+.75000	+.103370	+.526417	+.325966		
+.78125	+.103999	+.554570	+.327640		
+.81250	+.099887	+.539371	+.31663		
+.84375	+.096630	+.589125	+.30882		
+.87500	+.076380	+.560406	+.26439		
+.90625	+.057991	+.487497	+.272073		
+.93750	+.043291	+.422427	+.193723		
+.96875	+.050223	+.161186	+.209724		
+1.00000	+.056294	+.074027	+.24440		
+1.03125	+.092622	+.144428	+.298591		
+1.06250	+.099986	+.153376	+.316997		
+1.09375	+.102590	+.217040	+.323946		
+1.12500	+.102928	+.196521	+.324253		
+1.15625	+.104184	+.206836	+.320193		
+1.18750	+.104871	+.210590	+.330083		
+1.21875	+.103263	+.207073	+.325674		
+1.25000	+.102192	+.194471	+.322773		
+1.28125	+.103496	+.200091	+.326310		
+1.31250	+.101882	+.195161	+.321938		
+1.45000	+.101374	+.160414	+.320975		
+1.58750	+.100792	+.125899	+.321303		
+1.68250	+.100422	−.010891	+.318046		
+2.00000	+.102052	−.067175	+.327399		

Figure F3. (cont) Run 5 2/24/94 Raw Data

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